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Instrumentation for Field Studies of Urban Runoff

Research Report No. 42

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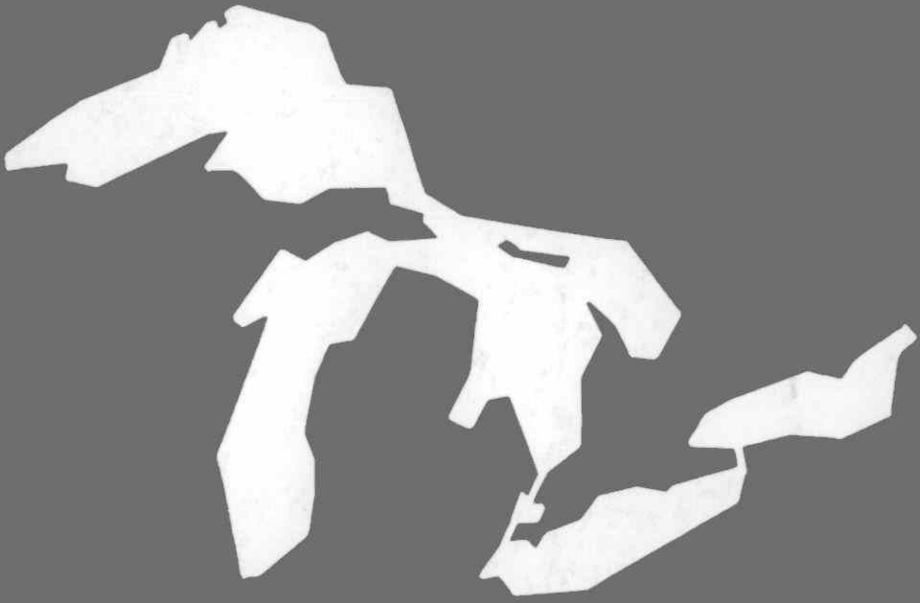

esearch Program for the Abatement of Municipal Pollution
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RESEARCH REPORTS

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INSTRUMENTATION FOR FIELD STUDIES OF URBAN RUNOFF

by

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RESEARCH PROGRAM FOR THE ABATEMENT
OF MUNICIPAL POLLUTION WITHIN THE
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ABSTRACT

The report examines instrumentation and monitoring techniques for field studies of urban runoff. In particular, the following types of instruments were studied:

recording precipitation gauges;
sewer flow measurement instruments; and,
automatic wastewater samplers.

After reviewing the literature and surveying the market, some of the promising instruments were acquired, tested in the laboratory and operated in the field for various time periods.

Individual instruments are discussed with regard to their technical data, accuracy and reliability. Recommendations for the selection, interfacing and installation of the instruments are given.

RÉSUMÉ

Le présent rapport traite des appareils et techniques de mesure pour l'étude sur le terrain de l'écoulement en milieu urbain, notamment des pluviomètres enregistreurs, des appareils de mesure du débit des eaux d'égouts et des échantillonneurs automatiques des eaux usées.

Après une étude bibliographique et l'inventaire des appareils disponibles sur le marché, on s'en est procuré quelques-uns, des plus prometteurs et on les a éprouvés plus ou moins longtemps en laboratoire puis sur le terrain.

Pour chacun, il est discuté des données techniques, de l'exactitude et de la fiabilité; on fait aussi des recommandations concernant la sélection, la connection et l'installation des instruments.

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CONCLUSIONS

The assessment of environmental impact of urban runoff on receiving waters requires detailed data on the precipitation - runoff processes. Such data are also needed for further development and application of urban runoff models.

The following phenomena are of major interest:

precipitation;
runoff flow rate; and,
runoff quality.

The precipitation data consist of the point precipitation and of the areal distribution of precipitation. Such information can be obtained from a network of several recording rain gauges installed within the studied area. The tipping bucket rain gauge (0.01 in) is particularly suitable for this purpose. A good time resolution, frequently five minutes or better, is required.

Runoff flow rates should be recorded continuously at one or more points. Whenever feasible, runoff flows should be measured at the outfall, outside the sewer system. Conventional constriction flow meters such as weirs (inexpensive, but block the transport of solids) or flumes (more expensive, but allow the passage of solids), can be used.

If it is necessary to measure inside the sewer system, and the sewer pipe is not frequently surcharged, an inexpensive trapezoidal weir without the bottom part or a flume (e.g. Palmer-Bowlus) is applicable. For frequently surcharged pipes, a dual free-pressurized flow meter such as U.S. Geological Survey Sewer Flowmeter should be used, or an acoustic flow meter.

The acceptable accuracy of runoff flow measurements is 5-10%.

Runoff quality is commonly determined by the laboratory analysis of grab samples collected in the field. Such samples are collected sequentially by automatic samplers. A sampling interval as short as 5-10 minutes may be required. The first sample should be collected as close to the beginning of runoff as practicable.

The desirable size of samples is about 1000 ml. Great care must be taken to avoid systematic errors in the sampling. The first step in this direction is to locate the sampler intake at a cross-section where the sampled medium is rather homogeneous. The capability of the sampling apparatus to collect solids should be evaluated, mainly with regard to the intake orientation and the intake nozzle and line velocities.

To reduce the loss of quality data owing to sampler malfunctions, two samplers may have to be installed and operated in parallel.

A good time synchronization between the recordings of the precipitation, runoff flow and sample collection must be ensured, best by recording all this information on the same chart or tape.

RECOMMENDATIONS

The evaluation of novel sewer flow meters and automatic samplers should continue on a reduced scale. Better publicity should be given to the proven designs of data collection systems for urban runoff studies.

1 INTRODUCTION

Increasing urbanization of Canadian society makes a dramatic impact on water resources in the affected areas. The large imperviousness of urbanized areas reduces the infiltration of rain water into the ground, and consequently, increases the surface runoff. At the same time, this increased volume of runoff water is polluted, and typically, is discharged into local receiving waters without any control. Uncontrolled discharges from combined as well as separate sewers are recognized as one of the major contributors to the lowering of water quality in rivers and lakes. The problem of assessing these sources of pollution and defining potential solutions for the control of urban runoff has been addressed by the Urban Drainage Subcommittee (UDS) of the Technical Committee for the Canada-Ontario Agreement on Great Lakes Water Quality.

Under the research programme of the Urban Drainage Subcommittee, an urgent need for urban runoff data was identified and several data collection projects were initiated. The collected data will serve for the assessment of pollution caused by urban runoff and combined sewer overflows, for the planning, design and operation of drainage systems, and also for the development, calibration and verification of storm water management models.

It became apparent in the preparatory stage of the UDS data collection programme that the demands on the accuracy and detail of the data are rather stringent and that the instrumentation to be employed in the data collection must be carefully selected to meet the programme objectives. The Hydraulics Research Division of the Canada Centre for Inland Waters was authorized to assess the suitability of various conventional instruments and techniques for data collection in urban runoff studies. Following a literature survey, selected instruments for the monitoring of precipitation, runoff quantity and quality (by sampling) were acquired and tested in the laboratory as well as in the field. The findings of these tests are presented in this report. Throughout the report, the emphasis is placed on the general and practical aspects of data collection. For the design of special data acquisition systems, additional references are cited.

The report should be of interest to government agencies, consulting engineers and municipalities engaged in urban runoff studies.

2 MEASUREMENT OF PRECIPITATION

In the precipitation-runoff process, the precipitation is the forcing function (input) and the runoff represents the response of the drainage system. Consequently, accurate monitoring of precipitation is very important, especially if these data are to be used as an input in a runoff simulation model.

Monitoring of precipitation consists of two tasks. The first is to obtain a representative sample at a gauge location. The second task is to estimate the amount and distribution of precipitation over an area (watershed) by means of gauges at a number of locations.

The literature on the measurement of precipitation is plentiful. For references, the reader is referred to Bruce and Clark [3], and Kurtyka [13]. In this report, only a brief summary of the techniques and instruments suitable for the monitoring of precipitation in urban runoff studies is given.

2.1 Requirements for Precipitation Data

The requirements for precipitation data depend very much on the purpose for which the data are collected. Most of the discussion presented below is concerned with precipitation data to be used as input data for detailed modelling serving for the design of sewer systems. The requirements for other purposes, such as general runoff studies, planning or operational levels of runoff modelling, are likely to be less stringent.

Point precipitation data: The depth of precipitation is typically recorded in the increments of 0.01 inch (0.25 mm). The required time resolution of precipitation data depends on the size of the watershed, and eventually, on the purpose for which the data are collected. Table 1 offers general guidelines.

Number of precipitation gauges: Linsley [15] recommends the use of at least two rain gauges even for the smallest watersheds. At least one of these gauges should be located within the watershed. Two gauges are sufficient for areas up to 4 square miles ($\sim$ 10 km^2), and for up to 20 square miles ($\sim$ 52 km^2), Linsley recommends three gauges. The

TABLE 1. RECOMMENDED TIME RESOLUTIONS OF PRECIPITATION DATA FOR URBAN RUNOFF STUDIES.

Watershed Type	Size Acres	 Hectares	Time resolution minutes
Small Experimental Watersheds (for model development or calibration)	10-300	4-120	1-2
Large Experimental Watersheds	500-3000	200-1200	5
Data Serving for Design	up to 3000 > 3000	up to 1200 > 1200	5-10 10-15
Data Serving for Planning	> 3000	> 1200	60

number of gauges, however, is clearly a function of the local conditions and for techniques of planning rain gauge networks of optimum density, the reader is referred to Eagleson [7].

2.2 Precipitation Gauges

2.2.1 Sensors

Several recording rain gauges suitable for urban runoff studies are available on the market. Most common are the tipping bucket and weighing gauges. The comparison of both gauges is presented elsewhere (see e.g. Linsley [15]). It is generally agreed (Smoot [25]) that the tipping bucket gauge is preferable in urban runoff studies, mainly because of its superior mechanism for actuating circuits and good accuracy of measuring rainfall of medium intensities. For high intensities (3.0 in/hr - 6.0 in/hr; 76 mm/hr - 152 mm/hr), the gauge may require calibration.

A short description of the tipping bucket gauge used by the Atmospheric Environment Service follows.

The gauge receiver consists of a 10-inch (0.254 m) funnel which collects rain water and drains into a bucket which is half of a two-bucket receptacle pivoted on a knife-edge. As the upper bucket fills to a specified amount (0.1 inch; 0.25 mm), the balance will tip and the lower bucket is brought into position under the spout and the filled bucket is emptied. Each tip of the bucket generates an electric impulse which is transmitted to the recorder.

The standard tipping bucket rain gauge is not suitable for measuring snowfall. The gauge may be adapted for snowfall measurements by inserting a small heater such as a light bulb inside the lower gauge assembly. Overheating should be avoided. It may also be necessary to add a windshield. However, it should be noted that snowfall monitoring is rather uncommon in urban runoff studies. For accurate snowfall measurements, a weighing gauge should be used.

2.2.2 Recorders

The output signal of the tipping bucket can be recorded by a variety of recorders located either in the proximity of the gauge, 5 - 300 ft (1.5 - 91.5 m), or at a distance of several miles. The latter case, data telemetering, requires a data transmission medium, such as leased telephone line or other two-wire circuit, radio, microwave or a combination of wire and radio link. Data telemetering devices fall beyond the scope of this report. For details, manufacturers of such equipment (e.g. Leupold & Stevens, Inc.) should be contacted.

Recorders located in the proximity of the precipitation sensor can be classified, for example, as follows:

a) Strip Chart Recorders
b) Magnetic Tape Recorders
c) Punched Tape Recorders

Strip chart recorders

A great variety of strip chart recorders are suitable for this purpose. Three typical instruments which were used in this study with success are described below.

Standard recorder - (used by Atmospheric Environment Service) - has a 24-hour chart with a 0.02" of rain (0.5 mm) by 10 minutes grid.

Advantages: Very cheap and reliable - standard product.

Disadvantages: Fine time resolution (one minute) virtually impossible to achieve; daily changing of charts is required.

Leupold & Stevens Type A recorder - A very versatile, reliable instrument which can be used to record simultaneously precipitation and two other phenomena such as water level and temperatures. The recorder, driven by an electric motor, yields good time resolution for chart speeds of 2.4 inches/hour (61 mm/hour) and higher. At the above speed, the chart lasts about two weeks.
Advantages: Infrequent attendance of the instrument (once per week, or even once per two weeks). Perfect time synchronization between precipitation and other phenomena recorded on the same chart.
Disadvantages: Source of AC (115V) power required unless driven by spring, in which case the time resolution of one minute becomes impossible.

Esterline-Angus portable recorder (Series A) - A very versatile recorder, spring driven, capable of recording up to two analog signals and two "yes - no" signals. The tipping bucket signal may be recorded in either of these modes. For good time resolution, the chart speed of 100 mm/hour (3.94 in/hr) is required.
Advantages: Perfect time synchronization between precipitation and other phenomena recorded on the same chart.
Disadvantages: Most expensive in this group.

All the strip chart recorders described above have one common disadvantage - their records are not computer compatible. The records have to be manually processed and data transferred on tapes or punched cards. This is a relatively minor task for a small number of stations, and/or when only severe storms are of interest. The situation is quite different in case of large metropolitan areas with numerous monitoring stations (typically 30, or even more). Then it becomes economical to use either magnetic tape recorders or punched tape recorders. A brief outline of the application of such recorders follows; a detailed treatment on this topic is beyond the scope of this report.

Magnetic tape recorders

The magnetic tape recorders are typically installed at a central receiving station and record the information transmitted from field instruments. Leased telephone lines are usually used as a data transmission medium.

The use of magnetic tape recorders in conjunction with individual sensors is less frequent. The city of Seattle used small cassette tape recorders to record precipitation. As in the former case, the instrumentation was specifically designed for this particular purpose.

Punched tape recorders

Punched tape recorders are used in two types of application. Firstly, for in-situ recording, and secondly as central recording units.

Commercial products for both applications are available. For in-situ recording, punched tape units are available e.g. from Fisher & Porter Co., A. Ott, Leupold and Stevens, Inc., and others.

For central recording, manufacturers of data processing equipment should be contacted.

An example of a sophisticated (and also costly, $40,000 - $50,000) data collection system for urban runoff studies is shown in Figure 1 (after Smoot [26]).

2.2.3 Location and installation of rain gauge

The location of the rain gauge receiver is very important for accurate measurement of the point precipitation. The following instructions were excerpted from the AES Instrument Manual 41 (Nov. 1952).

"The receiver should be located in an open area which is preferably somewhat sheltered but at the same time, it must not be close enough to surrounding objects to be "shadowed" by them. If practicable, the gauge should not be closer to objects than four times the height of the object, especially with respect to objects on the prevailing wind side of the gauge. Sites on a slope or with ground sloping sharply away in one direction (especially if this direction is the same as the prevailing wind) should be avoided. It is preferable to have the surrounding ground sodded."

The lip of the receiver is to be 29.5 inches (75 cm) above the ground level.

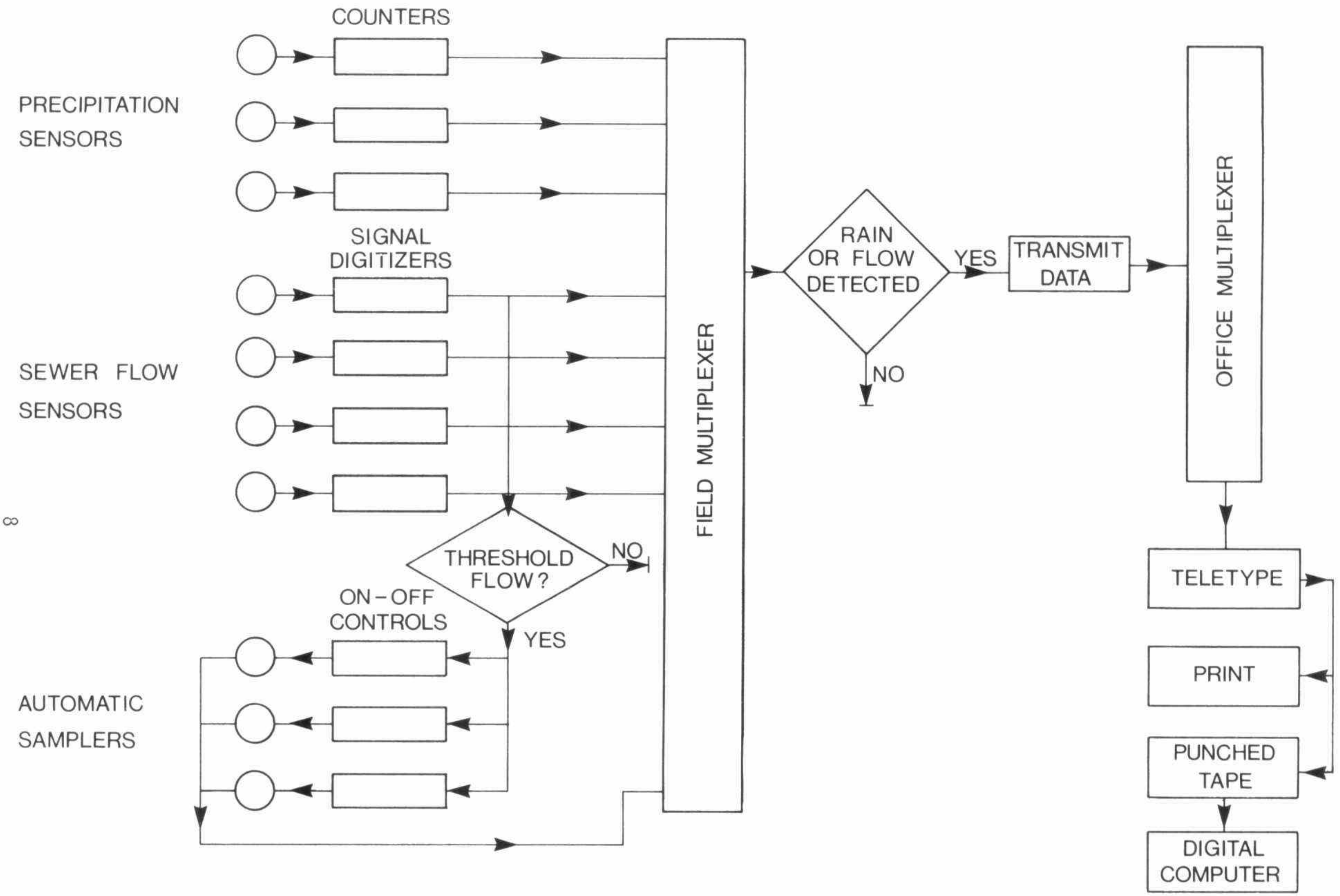


FIG. 1 EXAMPLE OF A COMPLEX DATA COLLECTION SYSTEM FOR RUNOFF STUDIES (AFTER REF. 26)

The above conditions are difficult to satisfy in urban areas. Feasible gauge sites are typically very limited, either because of "shadowing" effects of various objects or because of the threat of vandalism. The gauge site selection is usually based on a compromise between proper gauge exposure and adequate gauge exposure and adequate gauge protection against vandalism. According to Kurtyka [13], a poorly exposed rain gauge will underestimate the total precipitation by 5 to 80%.

3 SEWER FLOW MEASUREMENT

3.1 General Considerations

Field studies of urban runoff involve measurements of various sewer flows, such as sanitary flow, infiltration flow, combined sewage flow (i.e. a mixture of sanitary sewage and storm water) and storm water flow. The first two cases, sanitary sewage and infiltration flows, can be characterized as quasi-steady free flows. Consequently, the conventional flow meters (e.g. flumes) can be applied with good success. Flow monitoring is much more involved in the cases of combined sewage and storm water flows, which are measured either in the sewer system, or whenever possible, at the sewer outfall. Flow measurements within the sewer pipe network suffer from the following difficulties:

a) Varying flow boundary geometry causing flow non-uniformity.
b) Wide range of flows with rapid changes from virtually zero to the peak rate (unsteady flow).
c) Change from open-channel (free) flow to pressure flow (surcharging).
d) Contamination of the metered media by suspended solids and floating debris.
e) Space limitations (inside the sewer pipe and manhole structures).
f) Sewer environment - damp and corrosive.

It is essential that the flow meter should not interfere excessively with the sewer flow, to avoid sewer surcharging or the distortion of flow hydrographs by the presence and operation of the meter.

Most of the above-mentioned problems can be avoided when measuring at the sewer outfall, outside the sewer system.

3.2 Required Accuracy of Runoff Flow Measurement

Linsley [15] and Wenzel [33] both recommend that the urban runoff flow rates (the same would apply to wet weather combined sewage) should be measured with the accuracy of 5% at the readout point. The term accuracy is defined here as the estimated standard deviation of repeated measurements which is expressed as percentage of the adopted value, usually the mean. Using this definition and assuming a normal distribution of the measured values, the above accuracy criterion means that about 68% of all measurements should be within 5% of the adopted value and 95% of all measurements should be within 10%.

The U.S. Environmental Protection Agency specified [11] among the primary goals for development of a flow meter for storm and combined sewers the instrument accuracy of ± 5 to 8% at the readout point.

The required accuracy of flow measurements depends on the eventual use of the collected data. For design purposes (e.g. sewer pipe sizing), even an accuracy of ± 10 to 15% is acceptable, considering the other uncertainties involved. If the flow data are to be used for runoff research and runoff model calibration on small catchments, the accuracy of 5% is desirable, provided that other catchment parameters and precipitation are defined with a comparable accuracy. Large errors in the measured runoff will cause an erroneous calibration of the runoff model. Consequently, model simulations for design events of low frequency of occurrence may contain relatively larger errors than the calibration events of high frequency of occurrence.

Another requirement on sewer flow measurement is fast response of the measuring apparatus to the change in flow. On small catchments, say 50 acres (20 hectares), the flow may rise from virtually zero to the peak in about five minutes. On larger watersheds, this time will be correspondingly longer and may be estimated by calculating the time of travel of the full bore flow from the most distant point in the sewer system to the monitoring station.

3.3 Techniques for Sewer Flow Measurement

The available flow measuring instruments and techniques are examined in this chapter with regard to their applicability in urban runoff studies. Many of these instruments have been used by the Hydraulics Research Division of CCIW in a number of in-house and contract studies of urban runoff. The experience gained is given in this chapter.

3.3.1 Depth of flow measurement

This indirect method consists of measuring the depth of flow at a suitable cross-section in the sewer system and substituting this depth into an equation for uniform flow or the equation for the critical flow. In the former case, the knowledge of the sewer pipe roughness and invert slope is also required. The technique is very popular because of its simplicity. Most frequently, the Manning equation is used for the flow rate calculation:

$$Q = A \frac{1}{n} R^{2/3} S_f^{1/2} \tag{1}$$

where

Q = flow rate $[m^3/s]$
A = cross-sectional flow area $[m^2]$
n = Manning's roughness coefficient
R = hydraulic radius $[m]$
S_f= the friction slope ($S_f = S_b$, bottom slope, for steady uniform flow)

The inference of flow rates from depth measurements cannot be recommended for urban runoff studies because of large errors involved. Field experience from Baltimore (Johns Hopkin's University Urban Drainage Project) and Philadelphia indicate that the accuracy of this method is of the order 15 - 20%, well above the limits discussed earlier. Several main sources of error can be identified - non-uniformity and unsteadiness of the flow and the uncertainty in the estimate of Manning's n. With regard to the first two factors, non-uniformity and unsteadiness introduce extra terms into the dynamic equation, as can be noted below:

$$S_f = \underbrace{\underbrace{\underbrace{S_b}_{\text{steady, uniform flow}} - \frac{\partial y}{\partial x} - \frac{v}{g}\frac{\partial v}{\partial x}}_{\text{steady, non-uniform flow}} - \frac{1}{g}\frac{\partial v}{\partial t}}_{\text{unsteady, non-uniform flow}} \tag{2}$$

where

x = the longitudinal coordinate
y = the depth of flow (measured from the invert)
v = the velocity
t = time

The propagation of runoff flood waves through sewer pipes can be characterized as an unsteady non-uniform flow. For this condition, a unique stage-discharge relationship does not apply and is replaced by the loop-rating curve (see Figure 2). The flow rates calculated from Manning's formula will be underestimated for the rising stage and overestimated for the falling stage. Flow inferred from single stage measurements may be partially corrected for the non-uniformity and unsteadiness of the flow by a method described by Henderson [8].

Lastly, the estimate of Manning's n is another source of error. The value of n given in various handbooks varies significantly. For example, reference [6] gives Manning's n for concrete pipes ranging from 0.011 to 0.015. Furthermore, the friction coefficient also varies with the depth of flow and may be influenced by local form losses, such as losses at sewer pipes junctions, manhole structures or poor joints.

Huber [10] proposed to calculate flow rates from two simultaneous stage measurements using the dynamic equation and continuity equation written for unsteady non-uniform free flow. The aforementioned differential equations are replaced by difference equations, and these are solved for velocity. The method has not been tested in the field so far. The stage measurements have to be extremely accurate and perfectly synchronized Difficulties in estimating the roughness coefficient (Manning's n in this case) are also encountered in this case. Though the method represents a definite improvement of the single stage measurement technique, it is unlikely that a field accuracy better than 10-15% could be obtained.

Instruments for the measurement of liquid levels. A variety of liquid level sensors is available on the market. Only some of these instruments are applicable in sewer flow studies and those are described below. The following liquid level sensors are dealt with:

capacitance probe
dipping probe
floats
pneumatic probe
ultrasonic probe.

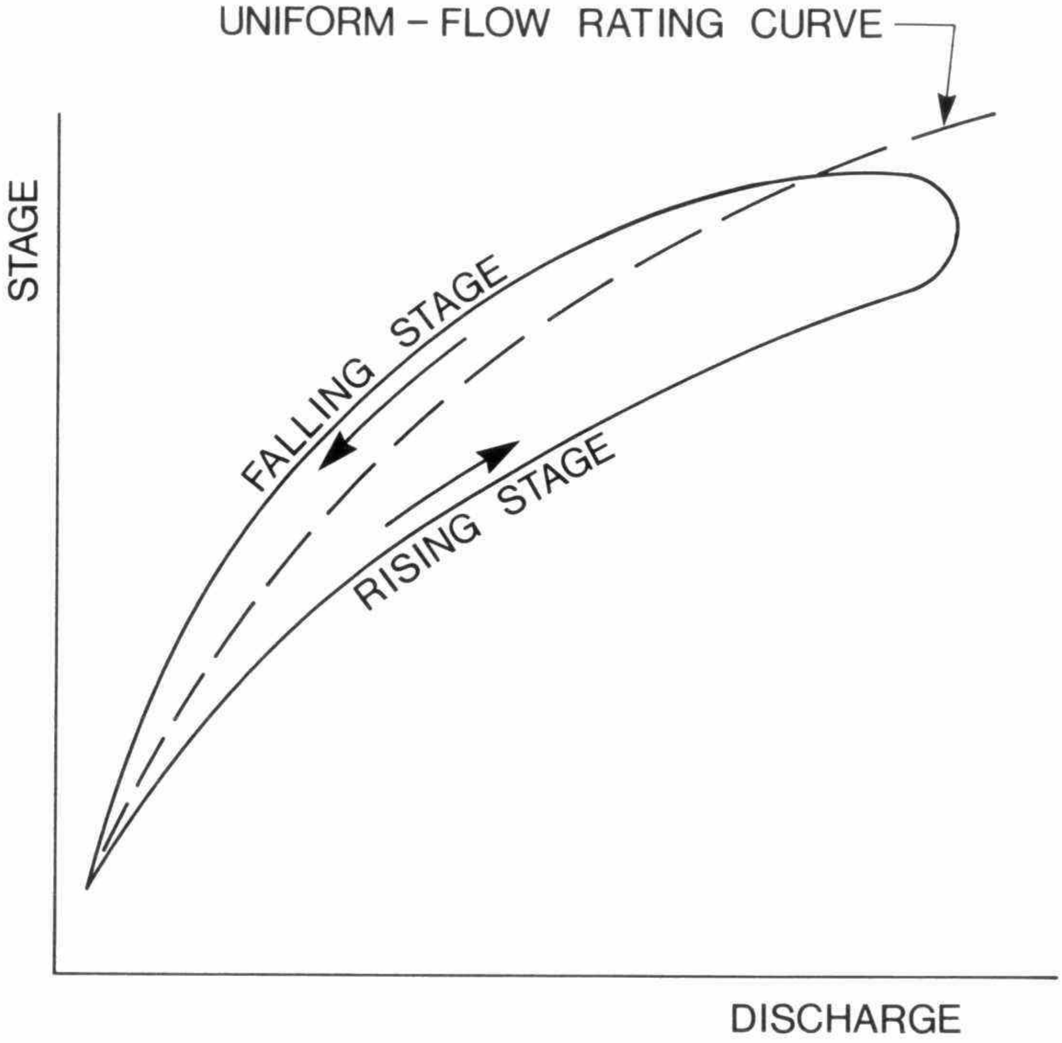


FIG. 2 A LOOP - RATING CURVE TYPICAL FOR PROPAGATION OF FLOOD WAVES THROUGH STORM DRAINS

Ideally, the sewage level sensor should meet the following requirements: good accuracy (1-2%); fast response to level changes; non-obstruction and non-interference with the flow; the readings should not be affected by the sewer flow velocity and sewage quality; the instrument should not get easily fouled; and, finally, the instrument should be reliable and capable of withstanding the sewer environment.

Accuracy of liquid level sensing. Liquid level sensors are typically used in conjunction with primary devices which sense the rate of flow. The flow measurement error, E_Q, then consists of two types of errors - the error inherent to the primary device, E_p, and the error caused by the erroneous liquid level measurement, E_{Qh}. In the worst case, both types of error would be added, thus

$$E_Q = E_p + E_{Qh} \tag{3}$$

The required accuracy of the level sensor depends also on the primary device used. In general, the rating curve of a primary device can be expressed as

$$Q = KCh^m \tag{4}$$

where

Q = the measured flow rate

K = a constant for the particular device

C = an experimental coefficient (C and K are sometimes combined together)

h = the head over the device

m = a constant for the particular device (e.g. m = 1.5 for Parshall flume, m = 2.5 for a V-notch weir).

The flow measurement error, $E_{Qh} = \frac{dQ}{Q}$, resulting from the error in the head measurement, E_h, $= \frac{dh}{h}$, can be calculated from Equation (3) as follows:

$$E_{Qh} = \frac{dQ}{Q} = \frac{mKCh^{m-1}dh}{KCh^m} = m\,\frac{dh}{h} = mE_h \tag{5}$$

Knowing the primary device error, the acceptable error of the depth of flow measurements can be calculated from Equations (3) and (5) as

$$E_h = \frac{E_Q - E_P}{m} \tag{6}$$

Typically, the required accuracy of the depth of flow measurements would be of the order 1 - 2%. This criterion is met by most of the instruments which have been considered.

Response time. Electronic and pneumatic gauges respond very quickly in the liquid level. The need to consider the level sensor response time may arise in the case of mechanical devices (floats), or when a stilling well is used. The fastest level rise velocity would be of the order .0015 - .0060 m/sec (.005 - .020 ft/sec).

Capacitance liquid level sensors. There are numerous capacitance liquid level sensors on the market. In the studies described here, the Robert-Shaw liquid level sensor (model 157) was used.
General description: The capacitance between the signal and ground electrode of a capacitor varies proportionately to the depth of submersion of the signal probe. The standard signal probe is a teflon coated steel rod (D = 1/4" = 6 mm). In sewer flow measurements, the rod was replaced by an insulated wire (see Figure 3). Two types of probes are generally available - a linear output probe and a characterized probe of which output is exponentially proportional to the measured head ($H^{3/2}$). The later type is suitable for use with weirs (rectangular and Cippoletti) and Parshall flumes. Rating curves of both types of signal probes are shown in Figure 3. The tested probes were exceptionally accurate (better than 1%) and their output was virtually unaffected by the ambient temperature changes as well as by the changing quality of the media. The probe can operate on a DC current (26.5 V ± 10%). In conjunction with the explosion proof transmitter, the instrument was operated in the sewer manhole structure for extended periods (six months) without any failures.

The field experience showed that the signal probe cannot be placed directly into the sewage flow, because it collects various floating debris and the readings are distorted. In combined or sanitary sewers, grease may also contribute to the fouling of probes. It is then necessary to place the probe either inside a stilling well or to build it into the side wall of a primary device.

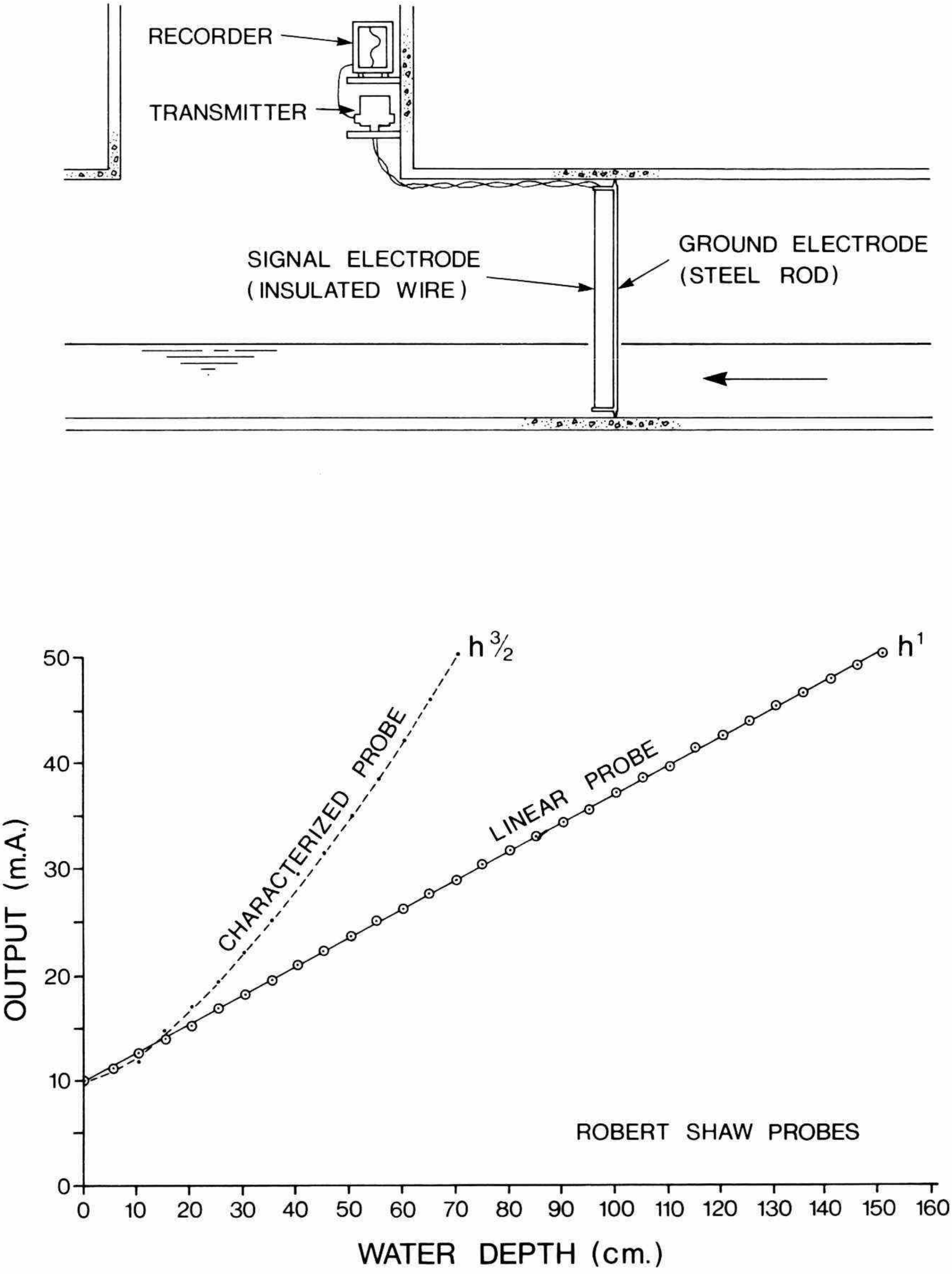


FIG. 3. CAPACITANCE LIQUID LEVEL GAUGE – AN INSTALLATION AND RATING CURVES.

Dipping probes. At present, these probes are manufactured only by the Manning Environmental Corporation. Two models have been used in related field studies - the portable Dipper unit (range 0'' - 60'', 0-1.5 m) and the Manning Dipper Transmitter.

General description: A thin stainless steel probe is lowered on a wire controlled by a precision motor. The probe makes a contact with the surface of the liquid and retracts slightly, then repeats this cycle. Any change in the liquid level will result in a shortening or lengthening of the unwound wire. Such a change is then converted into a linear analog signal.

The portable unit is very compact, battery operated and has a circular chart recorder (one or seven days). The time resolution of this unit does not meet the typical requirement for runoff studies. During the six months of operation of this unit, several breakdowns occurred and the instrument had to be repaired in the electronics workshop.

Dipper transmitter. This is a very versatile instrument which operates with either 12V DC or 120V AC current. The instrument has a three-way range switch which allows a choice of an output signal proportional to the full scale of the transmitter, half-scale or quarter-scale. The transmitter output signal can be recorded by an analog recorder. The manufacturer can supply a special recording and control unit - "Manning Total Flow Computer". This unit converts the dipper output into a flow proportional signal, integrates the flow and activates a sampler after a preselected volume of liquid has passed through the installation.

The dipper transmitter was installed and operated at two locations. During this period, both units required frequent maintenance and one of the units had to be factory repaired. The accuracy of the instrument tested was better than ± 4 mm.

Float liquid level sensors. Mechanical liquid level monitors which use floats as sensors are the oldest instruments used for liquid level monitoring. They are very reliable, inexpensive, and easy to maintain. Among the disadvantages of these instruments, one could name the need to construct a stilling well in many situations and also the need to record the displacement of cable-suspended floats by a mechanical recorder which does not accept electric output signals from other instruments. Therefore, mechanical level recorders cannot be easily incorporated in a data acquisition system with a single electronic recorder.

Two makes of float liquid level recorders were used in this study - Leupold & Stevens, and Ott. A brief description follows:

Leupold & Stevens water level recorder (Type A) is a mechanical water level recorder which is typically operated with a cylindrical float located in the stilling well, or it can be operated with a scow float (see Figure 4). The instrument accuracy is better than 0.01 ft (3 mm) for the standard float size; it can be further improved by using an oversized float. The instrument recorder is driven either by a weight, or preferably, by a synchronous motor. Only in the latter case can the required time resolution of the record (one minute) be achieved. The chart speed used in this study was 57.6 inches (1.46 m) per day. A 25-yard (22.9 m) strip chart then lasts about 15 days.

The instrument can be equipped with two optional sensors - a temperature sensor and a precipitation sensor. The temperature sensor measures either air or water temperature. The precipitation sensor is a tipping bucket rain gauge. The L & S recorder used in this study was modified by adding an event pen to record the operation of an automatic sampler. The precipitation as well as temperature are recorded on the same chart as water levels, thus ensuring a perfect time synchronization of the records.

The Leupold & Stevens recorder was found very reliable. During the 14 months of operation the instrument never failed and regular servicing once every 10-15 days was found adequate.

Ott Vertical water level recorder - The instrument operates on the same principle as the previous one. By using an oversized float, the accuracy of ± 1 mm was achieved. The recorder chart is driven by a spring. The highest chart speed is about 5/8" (155 mm) per hour - rather low. At this speed, the chart has to be changed every 24 hours.

In this study, the instrument was found very reliable and accurate. The time resolution of the records was, however, poor and charts had to

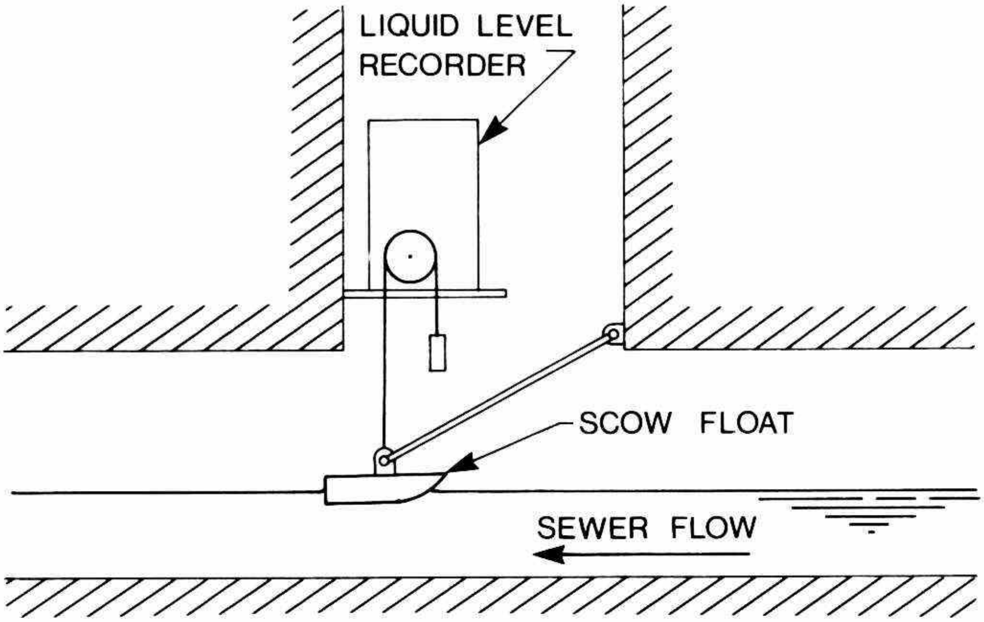


FIG. 4. SCOW FLOAT INSTALLATION

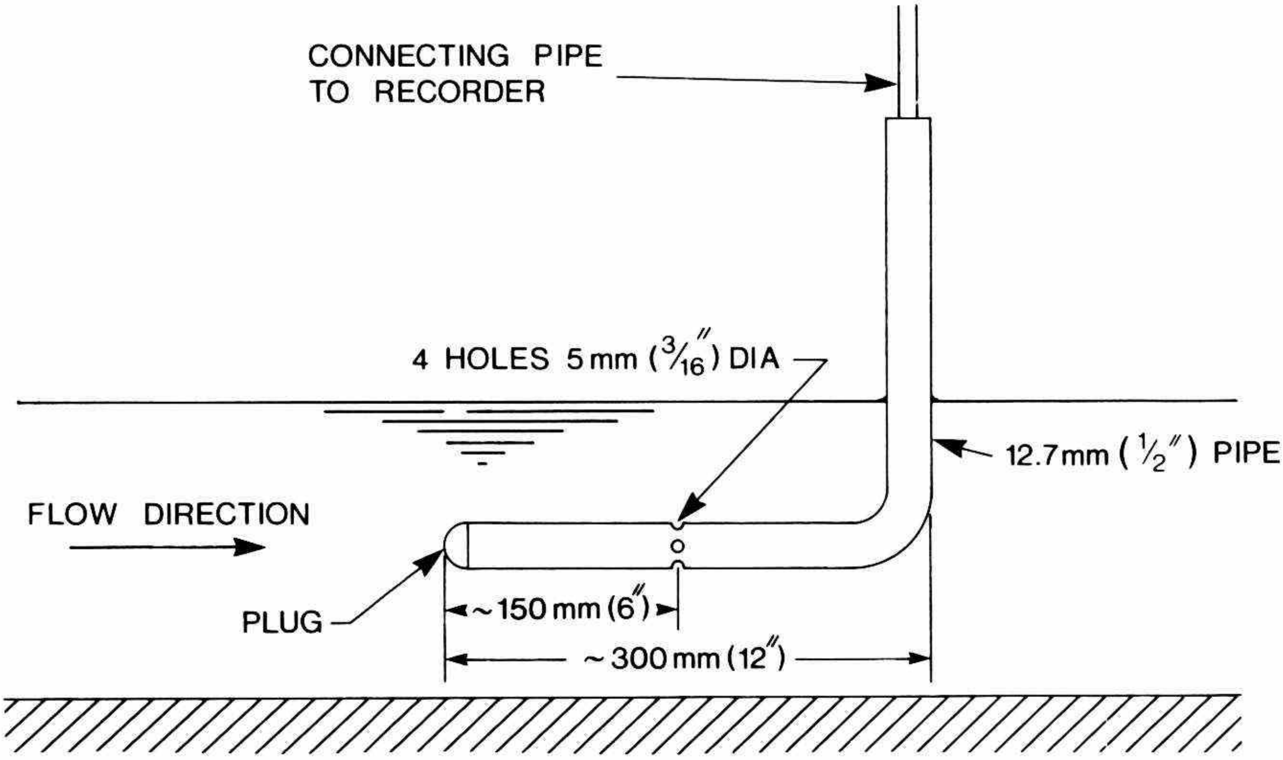

CONNECTING PIPE TO RECORDER
4 HOLES 5 mm ($^{3}/_{16}''$) DIA
12.7 mm ($^{1}/_{2}''$) PIPE
FLOW DIRECTION
PLUG
~150 mm (6")
~300 mm (12")

FIG. 5. AIR – BUBBLER INSTALLATION IN A FAST FLOWING MEDIA.

be changed every day. For these reasons, the Ott vertical water level recorder was found unsuitable for urban runoff studies. Other models made by Ott (models X and XX) have continuous strip charts, but the highest chart speed is only 20 mm/hr. The required time resolution of one minute cannot be achieved.

Frequently, the floats of mechanical level recorders are placed in a stilling well which is connected by a small tube to the sewer pipe. The response time of water level in the stilling well depends on the cross-sectional area of the stilling well, A_{sw}, cross-section of the connecting pipe (actually its hydraulic resistance), A_{cp}, and level-rise velocity at the monitoring cross-section. Though the ratios A_{sw}/A_{cp} are commonly as high as 100, it is recommended that runoff studies not exceed the value of $A_{sw}/A_{cp} = 20:1$, in order to maintain a fast response of the stilling well to the water level changes.

Scow floats. In most flow monitoring installations in sewer systems, space limitations do not allow the installation of a stilling well. Conventional level recorders can then be modified by replacing the standard float by a scow float (see Figure 4). The cable connecting the float to the recorder has to be properly guided to avoid malfunctions (cable "jumping" the pulleys inside the recorder).

Commercial products using quasi-spherical (or other shape) floats as scow floats are available. Among these are Fisher & Porter (Models 10F1275 and 10F1276), Badger Meter (ML-MN Transmitter), Leopold (Float-in-Flume Transmitter), NB Electronic (Series F Manhole Meter) and Pennwalt Instream Flow Meter-Transmitter (Series 83-030). In case of all these instruments, the scow float is held in place by a pivoted arm. The float movement produces angular movements of the arm and the shaft on which it is supported. The movement of the shaft is then converted into an electronic (or pressure) output. Such an arrangement is more reliable than previously described cable-suspended scow floats.

Pneumatic water level gauges (air bubblers). Pneumatic level gauges are frequently used for measurements in sewers. These instruments are relatively simple, do not obstruct flow and the sensor can be installed several hundred feet from the recorder. Pneumatic gauges are the only instruments suitable for operation in surcharged sewers. A number of these gauges are available on the market, e.g. Arkon, Bristol, Lug, Ott, and Leupold and Stevens.

General description: Gas (frequently air or nitrogen) is forced, at a low rate of flow, through a thin tube (dip tube) immersed into the measured liquid. The gas pressure at the end of the tube then equals the static pressure due to the weight of liquid column above the point of gas discharge, and thus is a measure of the depth of the liquid. The transmitter output (pressure) is either recorded directly, or first converted to an electronic signal and then recorded. The latter alternative is preferred, if a multi-channel recorder is used for simultaneous recording of several phenomena and the compatibility of recorded signals is required. The pressure to electronic signal converters are made e.g. by Bailey, and Badger Meter.

For fast flowing liquids, say $v > 0.5$ m/s ($v > 2$ ft/s), it is recommended to protect the dip tube by a simple "stilling well" in the form of a concentric sleeve pipe, or better, to use an arrangement analogous to the laboratory static tube (see Figure 5). The latter arrangement is recommended by Arkon Industrial Instruments, manufacturers of bubblers [1]. Without such protection, the bubbler readings could be affected by the velocity of a fast flowing media.

Pneumatic liquid level gauges are the only instruments usable for the measurement of pressurized flows in sewers, as described later. These gauges are particularly suitable for winter operation, e.g. Ott's instrument remains operational at temperatures as low as -20^{o}C.

For urban runoff studies, the pneumatic gauge output should be recorded by a strip chart recorder having adequate chart speed, and whenever possible, the use of the bottom portion of the total pressure range should be avoided. In that portion of the total range, the relative accuracy of the instrument is the lowest (about ± 10%).

Ultrasonic liquid level sensors. Ultrasonic sensors are unique with respect to non-interference with the flow - no parts of the instrument are in a direct contact with the measured liquid. A Wesmar ultrasonic sensor (SLM9 Ultrasonic Level Monitor, temperature-compensated) was used in this study with success.

General description: The sensor located above the target material (sewage) emits acoustical energy directed towards the material. The reflected acoustical energy (echo) is detected by the same sensor and converted to an analog voltage or current, proportional to the distance between the sensor and the target. According to the manufacturer the accuracy of the Wesmar Probe is better than 1% of the total range (i.e. 30 mm). A calibration curve of the instrument employed is shown in Figure 6. For the instrument tested, the standard error (accuracy) of the depth measurements was estimated as ± 4 mm.

The instrument can operate either on AC or DC power. It can be equipped with optional alarm points which can be used to actuate an automatic sampler or other equipment. Two types of probe outputs are available - the linear and exponential (exp. = 1.5).

When selecting a location for the sensor, two conditions should be met. Firstly, the wetting of the radiating face should be avoided; secondly, the sensor should be located above a fairly smooth water surface to avoid spurious reflections. If necessary, the sensor is placed inside a stilling well.

The SLM9 - Wesmar probe has been installed and operated successfully in a combined sewer for about four months.

The basic characteristics of liquid level sensors discussed in this section are summarized in Table 2.

TABLE 2. CHARACTERISTICS OF SELECTED LIQUID LEVEL SENSORS

Liquid Level sensor	Application		Typical Installation			Input Power Options (Sensor only)		
	Free Flow	Pressure Flow	Directly in Sewer	In Sewer but with some protection	In a Stilling Well	DC	AC	Other
Capacitance P.	X	-	-	X	X	X	X	-
Dipper P.	X	-	X	-	-	X	X	-
Floats	X	-	X (scow fl.)	-	X	-	-	none required
Pneumatic P.	X	X	X	X	-	X	X	X (comp. gas)
Acoustic P.	X	-	X	-	X	X	X	-

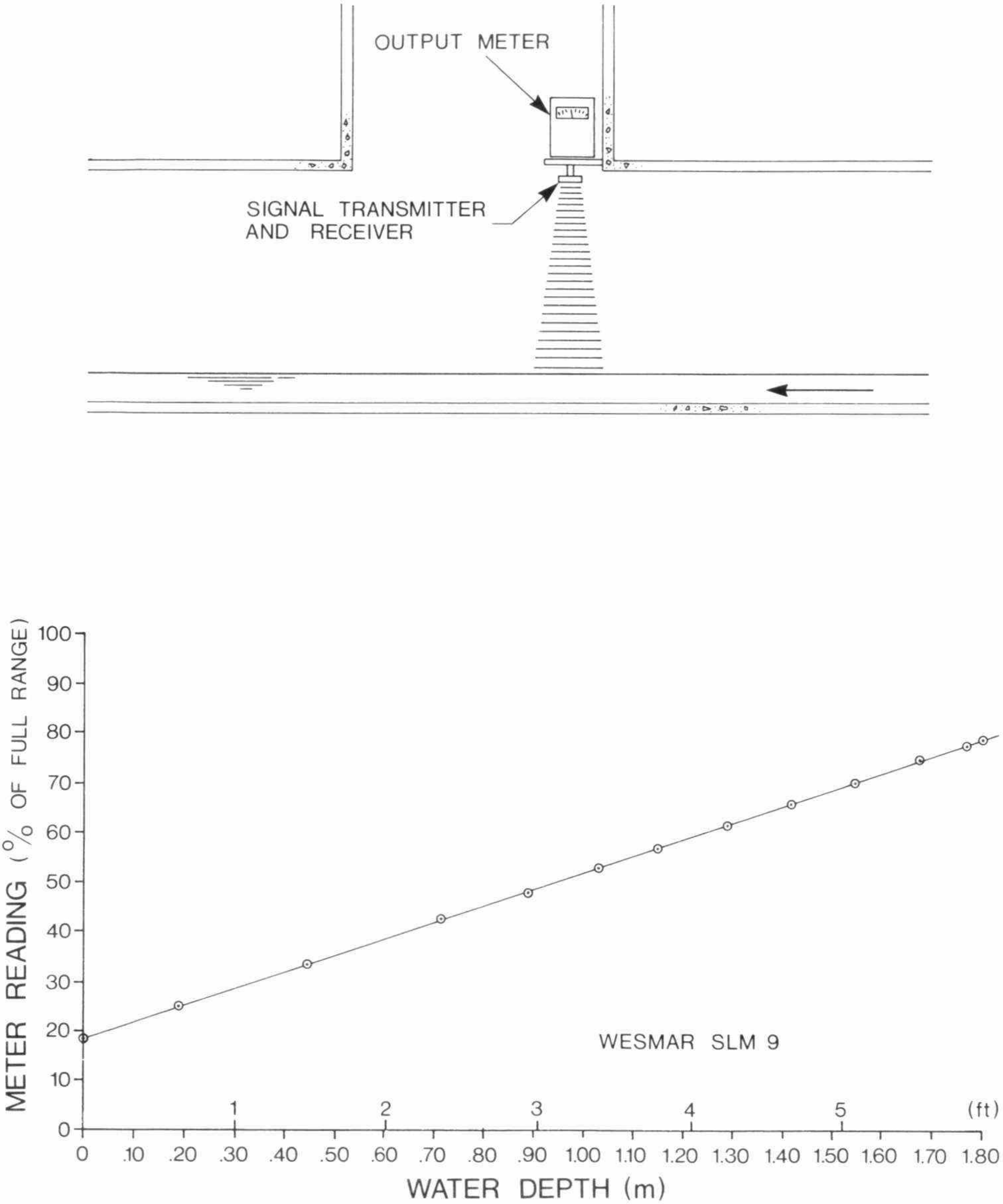


FIG. 6 ACOUSTIC LIQUID LEVEL GAUGE – AN INSTALLATION AND RATING CURVE.

3.3.2 Depth and point velocity

In this method, the flow rate is derived by multiplying the flow area (inferred from the pipe geometry and the depth of flow) by the measured velocity of the flow. The velocity should be the mean velocity in the cross-section, or the relation between the measured and the mean velocity has to be known and taken into account. The latter requirement may be difficult to satisfy, with the required accuracy, under the conditions of unsteady flow.

For the velocity measurement, the following instruments were either used in practice or are available on the market and could be employed in sewers:

current meters (mechanical as well as electronic)
tensometric (drag) velocity probes - unprotected
Pitot tube

The first two types of instrument do not work well in sewers. They tend to get clogged or their readings are distorted by floating debris.

Some success was had with Pitot tubes in a Chicago study [20]. A number of Pitot tubes were installed in a sewer cross-section, their readings were averaged and the average velocity was used for the calculation of flow rates. The clogging of the Pitot tubes was prevented by regular purging of the tubes by compressed air.

Commercial sewage level and velocity meters - there is a commercial product (Bristol Series 840 L/V Monitor) which measures simultaneously the depth and velocity of sewage flow in sewers ranging from 4 ft to 20 ft (1.22 m - 6.10 m). The velocity is continuously measured by a tensometric sensor. To clean the sensor, it is retracted at regular time intervals (normally 15 minutes) through a tight fitting wiper sleeve. The liquid level and sensor submergence are measured by an air bubbler.

The manufacturer quotes the typical accuracy of the velocity probe ± 5% and the level sensor ± 1/4 inch (± 6 mm). There is, however, another source of error due to the difference between the mean flow velocity and the velocity measured by the probe. It is conceivable that the L/V Monitor could meet the accuracy criterion since an analogous technique applied to river gauging yielded discharge measurements within ± 5% of the adopted values [27]. The L/V Monitor is the only instrument discussed in this section which has a potential for use in runoff studies.

3.3.3 Flow rates derived from specific energy measurements

In Cincinnati studies [30], the measurements of the depth of flow and of the velocity (actually of the velocity head) were combined into the single measurement of specific energy E defined as

$$E = y + \frac{v^2}{2g} \tag{7}$$

where

y = the depth of flow
v = the mean velocity in the cross-section
g = the acceleration due to the gravity.

For a particular location, the curve discharge vs specific energy was derived from Manning's equation and this curve was then used for determining the discharge (see Figure 7). The specific energy was measured by a pneumatic pressure sensor (bubbler) pointing upstream.

No information on the accuracy of the technique is available. It is evident, however, that the technique has the same shortcomings as the method 3.3.2 inference of flow rates from the depth of flow and an equation for uniform steady flow. Furthermore, the monitored point velocity differs from the mean velocity of the flow, thus, introducing another source of error. The flow measurement technique based on the specific energy measurements is not, therefore, recommended for the field studies of urban runoff.

3.3.4 Depth and average velocity along one or more chords

Because of difficulties in relating the point velocity to the mean velocity, the point velocity is replaced in this method by an average velocity along a chord to the sewer pipe. Such an arrangement is shown in Figure 8. Depending on the size of the pipe, it may become necessary to measure along two or even three chords.

The average velocity is measured by an acoustic sensor. Two such instruments are available on the market - Westinghouse LE acoustic flow meter and Badger ultrasonic flow meter. While the first system is

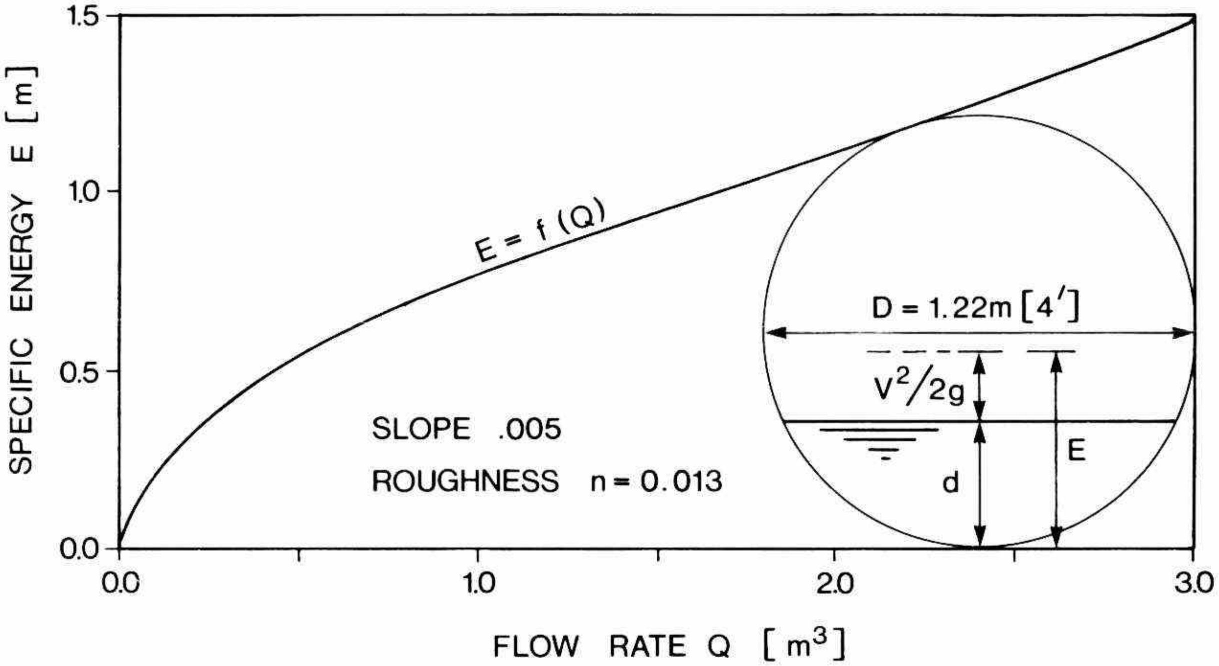
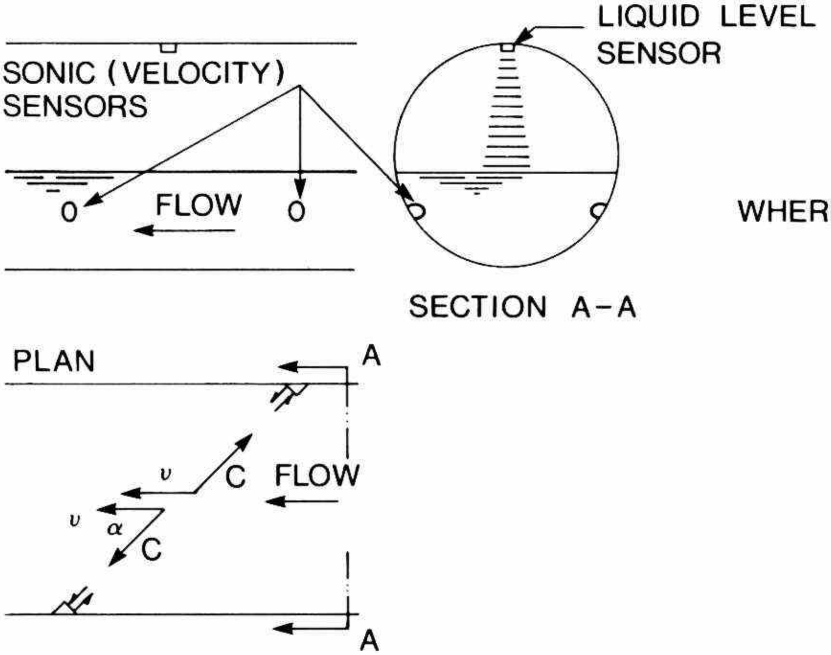


FIG. 7. SPECIFIC ENERGY vs. FLOW RATE (DERIVED FROM MANNING EQUATION FOR A 4ft PIPE).



$$v = \frac{C\ (fd - f\mu)}{(fd + f\mu)\cos\alpha}$$

WHERE

v = Fluid velocity

C = true sonic velocity of the fluid

α = beam angle across the stream

fd, $f\mu$ = measured down-stream and upstream pulse transmission frequencies, respectively

Q = vA WHERE Q = FLOW RATE

A = FLOW AREA

FIG. 8. OPERATING PRINCIPLE OF AN ULTRASONIC FLOW METER

primarily ment for large permanent installations (1973 price $60,000 plus), the second instrument is applicable in smaller installations. The Badger meter was field tested in a sewer interceptor in Milwaukee. Some difficulties were experienced in the initial testing phase with suspended air bubbles (size in the order of microns) which affected the meter readings.

The price of the instrument consisting of two velocity probes, a level gauge and a control unit, is of the order of $20,000 (1973 price). The instrument has to be installed by the factory personnel. The manufacturer claims that the flow rates can be measured by this instrument with accuracy of ± 2%.

According to Kirkpatrick [11], the Badger ultrasonic flow meter seems to meet most of the EPA specifications for a sewer flow meter.

3.3.5 Measurement of depth of flow and mean velocity

From the theoretical point of view, this is the most exact procedure. Unfortunately, no commercial instruments are available at present for the measurement of mean velocity.

The mean velocity can be measured by a tracer technique - using the time of travel method. In this method, a slug of tracer is injected into the sewer flow and the tracer concentration is monitored by two probes located downstream and spaced some distance apart. The average flow velocity is determined from the measured time of slug travel and the known distance between both probes. The most economical tracer is salt. Conductivity probes are used for tracer monitoring.

Typically, the tracer techniques are applied manually, which excludes them from use in urban runoff studies. The feasibility of automatizing this technique was studied by Preul [22]. In his proposal, the time of travel of small slugs of salt (injected at regular time intervals) would be determined from the simultaneous recording of the output of two conductivity probes. The main technical problem encountered in this case was the fouling up of the probes.

3.3.6 Measuring weirs

Measuring weirs are conventional instruments (primary devices) used for flow monitoring. Typically, sharp-edged weirs of various geometries are used. The following types of weirs were used successfully in sewer studies (see Figure 9):

a) rectangular weir
b) V-notch weir
c) vertical slot weir
d) trapezoidal weir without bottom part

Main advantages of the weirs are low cost, good accuracy (about ± 2-5%, except for very low flows) and high reliability.

Among disadvantages are the reduction in sewer pipe capacity, the accumulation of solids for type a) and b), the possible distortion of flow hydrographs because of the presence of the weir, and limited operational range because of surcharging and submergence.

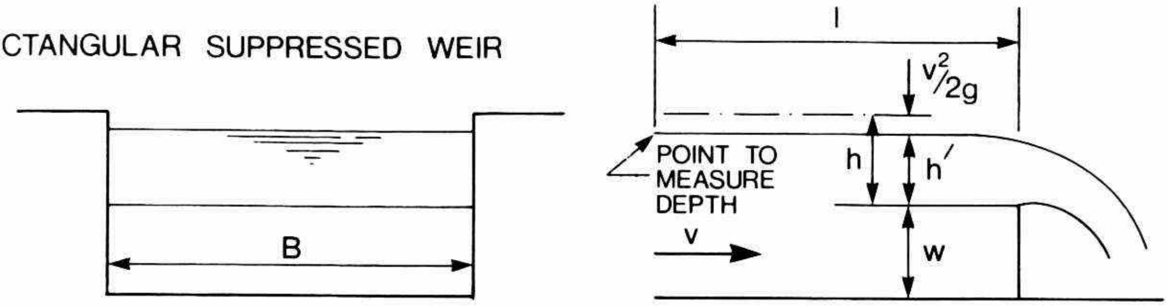
A brief description of the individual types of weirs and their applicability to sewer flow measurements follows. Further information on rectangular and V-notch weirs can be found in ref. [2]; on vertical slots, in ref. [9].

a) Rectangular weir - though the simplest one to manufacture, it is not recommended for installation in sewer pipes, because it reduces considerably the pipe capacity and causes accumulation of solids immediately upstream of the weir. The rectangular weir is rather insensitive to low flows. This type of weir is recommended only for installations at the sewer outfall, outside the sewer system. A typical installation is shown in Figures 9 and 11.

b) V-Notch weir - causes a larger constriction of the flow area than the rectangular weir. This results not only in good measuring sensitivity at low flows, but also in considerable reduction of the pipe capacity. Damming of sewage flows and solids deposition upstream of the weir are the main drawbacks. Consequently, only an installation at the outfall is acceptable. A typical installation and a 90° V-notch weir calibration curve are shown in Figure 9.

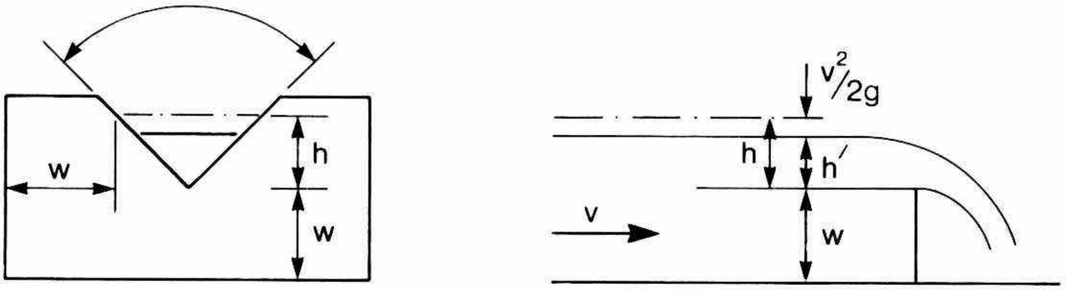
c) Vertical slot weir - allows the transport of solids through the installation. The rating curve of this weir may be affected by the pipe slope and roughness, particularly for wide slots and low flows. An example of a vertical slot weir installed in a circular storm drain is shown in Figure 10.

a) RECTANGULAR SUPPRESSED WEIR



RECOMMENDED GEOMETRY: $w = 2h_{MAX}$, $l = 4h_{MAX}$

b) 90° V - NOTCH WEIR



RECOMMENDED GEOMETRY: $w = 2h_{MAX}$

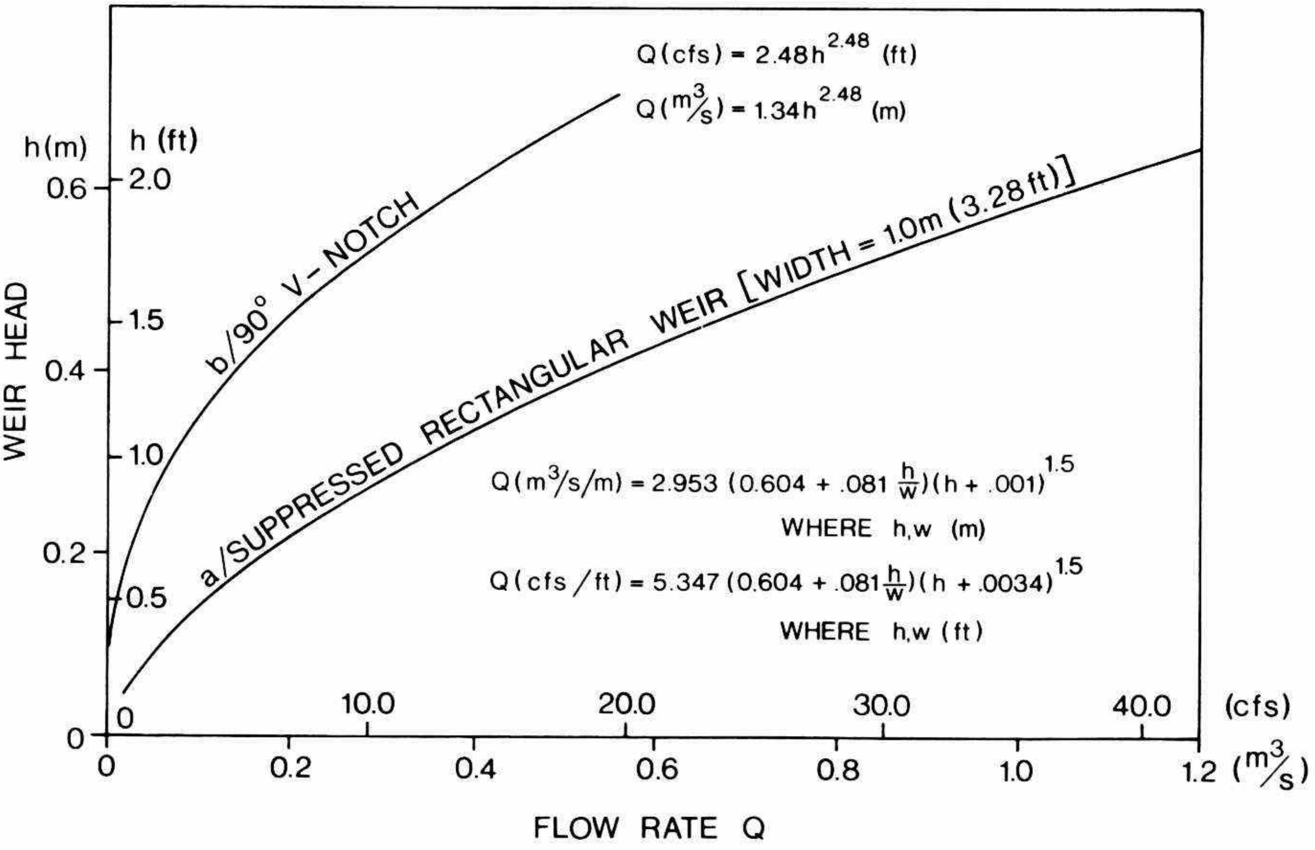
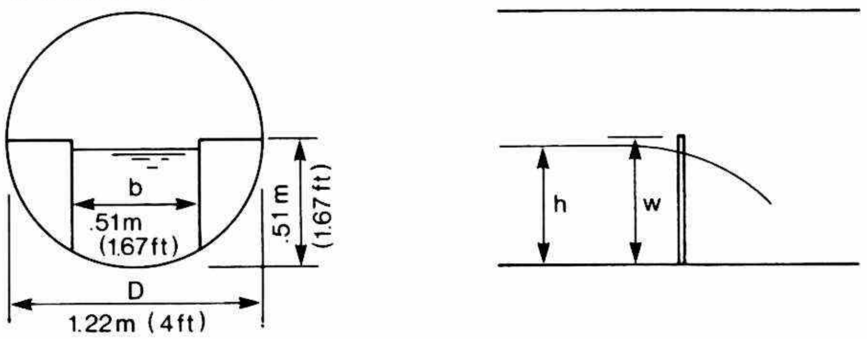
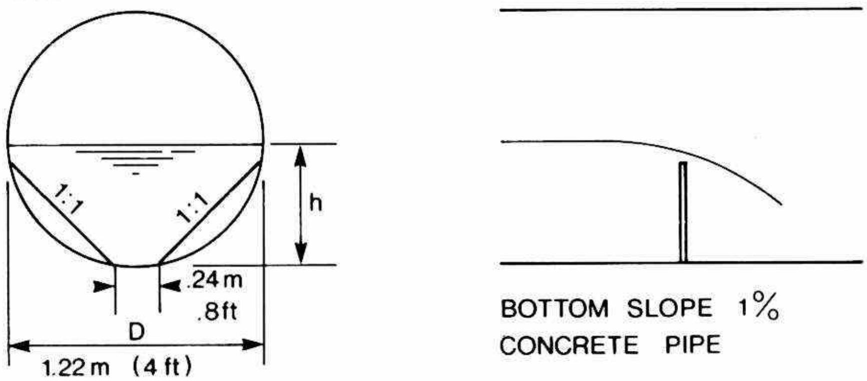


FIG. 9. CHARACTERISTICS OF RECTANGULAR AND V - NOTCH WEIRS.

(a) VERTICAL SLOT WEIR



(b) MODIFIED TRAPEZOIDAL WEIR



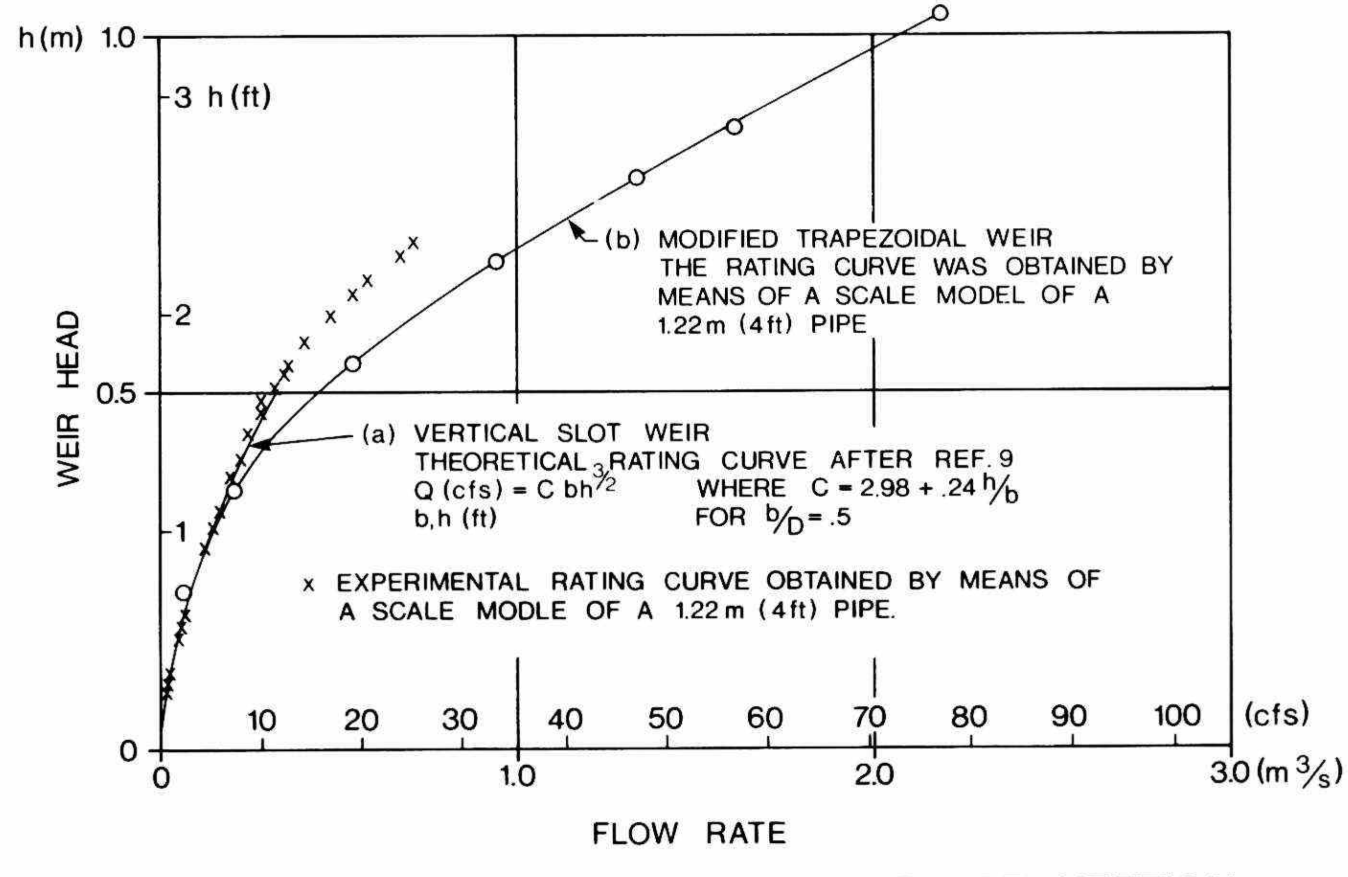


FIG. 10. EXAMPLES OF RATING CURVES FOR VERTICAL SLOT AND TRAPEZOIDAL WEIRS.

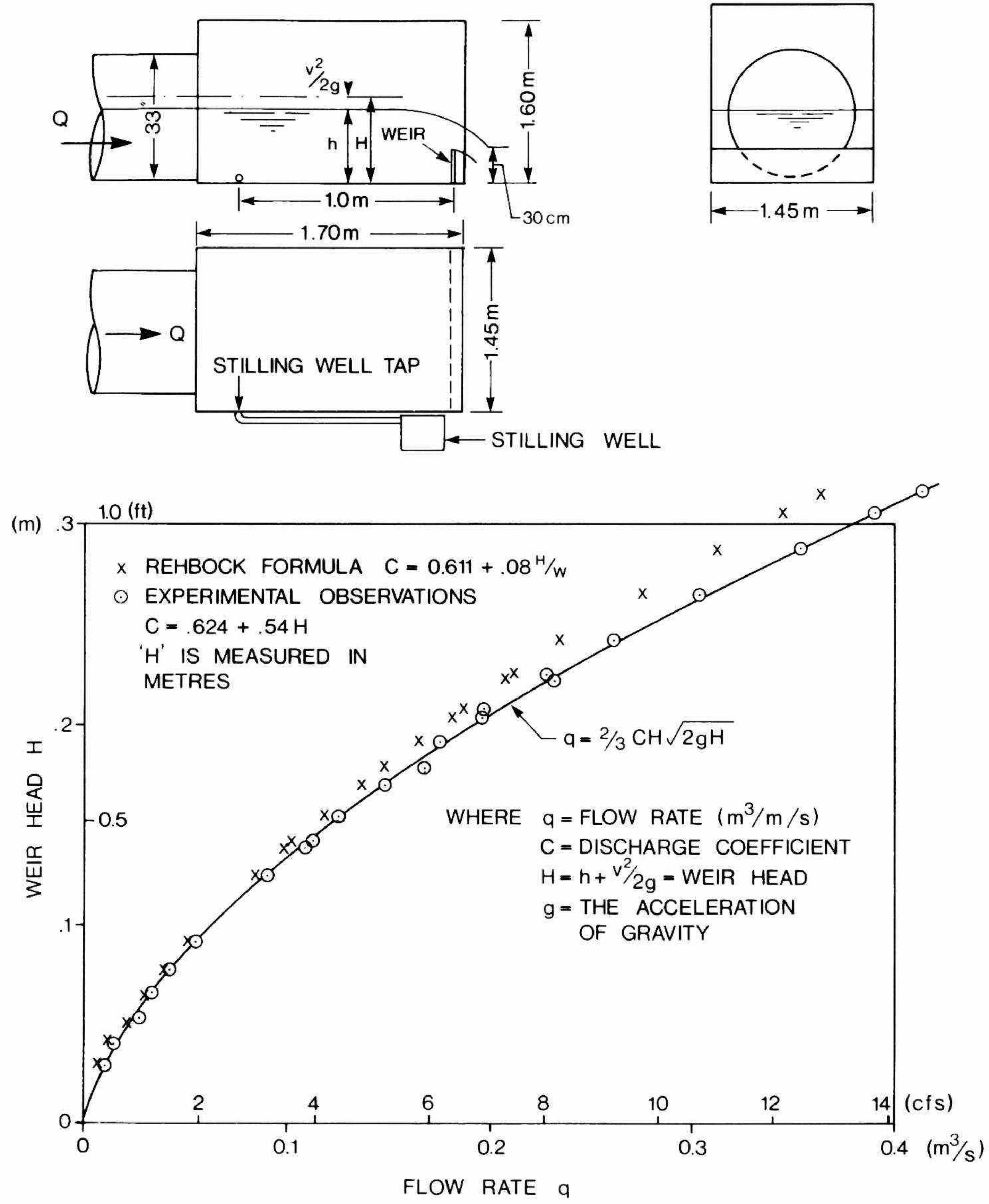


FIG. 11. RATING CURVE FOR A RECTANGULAR WEIR INSTALLED AT THE SEWER OUTFALL.

d) Trapezoidal weir without the bottom part - sometimes called a V-notch weir with the apex below the pipe invert, functions in a similar way as the vertical slot. It allows passage of solids, does not obstruct the flow excessively and can be designed to start to control the flow at smaller depths than the vertical slot. The weir rating curve may be affected by the pipe slope and roughness, particularly at low flows. This weir, as well as the vertical slot, may be installed directly in the sewer pipe. The former type is preferred. A typical installation and a rating curve are shown in Figure 10.

Errors in flow measurements by weirs. Assuming that the weir is precisely manufactured and properly installed and operated, two main sources of error are: (a) the error in the weir rating curve, and (b) the error in the weir head measurement.

Weir rating curves are either adopted from literature, or derived experimentally for a particular installation. The rating curve may be adopted from literature only in those cases when the intended installation and the point of head measurement are identical to those described in the literature. In other cases, it is better to have the monitoring facility calibrated. To illustrate this point, the rating curve for a rectangular weir suitable for installations at the drainage outfalls is shown in Figure 11 together with the rating curve for the same weir, but placed at the end of a rectangular trough (flume). For identical weir heads, the difference in the calculated flow rates could be up to 10%.

The accuracy of weir head measurements is discussed in Section 3.2. Typically, the overall accuracy of a calibrated weir installation is better than ± 5%, except for very low flows.

Measuring weirs installations. When selecting a location for weir installations, considerations have to be given to the surcharging of the sewer pipe (particularly after the pipe capacity has been reduced by the weir) and to the tail water levels. For surcharged pipes and/or high tail water levels, weirs become inoperational.

Typically, the head is measured four times the maximum weir head upstream of the weir. Weir structures are made of various materials, such as wood, bricks, concrete, steel, aluminum. Only the overflow edges are made of non-corrosive metals; aluminum is used most frequently.

Measuring weirs are best used at the sewer outfalls, outside the sewer system. In such cases, the problems with sewer surcharging and weir submergence can be avoided. For in-sewer installations, the trapezoidal weir with open bottom or the vertical slot are applicable, though with some limitations.

3.3.7 Measuring flumes

A measuring flume creates a constriction in the channel cross-section. If the downstream flow conditions do not affect the flow through the flume, then a definite relationship exists between the upstream depth and the flow through the facility. Flumes offer the same reliability and accuracy as weirs. Flumes are considerably more expensive than weirs, but on the other hand, create smaller head loss than weirs and remain operational even for the downstream depth of flow reaching about 80% of the upstream depth. Sewage solids pass freely through flume installations.

Hydraulic characteristics of flumes. Measuring flumes can be classified as tranquil flow measuring flumes and critical flow measuring flumes. The latter ones are more popular because the flow is then a function of the upstream depth only, as described for open channel flow by the following equation [31]:

$$Q = C_d \; K \, b \, h_1^{\;n_1} \tag{8}$$

where

C_d = the coefficient of discharge
K = a constant
b = the width of the throat
h_1 = depth of flow upstream from the flume
n_1 = a coefficient (a constant for a particular flume; $n \simeq 1.5$ for the Parshall flume)

Types of measuring flumes. Flumes of various geometries are used in practice. Some flumes have bottom contraction (hump), others not. The former ones are more popular in sewer studies, because they can be easily inserted into existing sewers and held in place. Also the error in the head measurement caused by standing water is eliminated in this case.

Flume throats of various shapes are used, e.g., rectangular, trapezoidal, semicircular and composite shapes (see Figure 12). The flumes with rectangular throats are rather common. They are simple to manufacture and their rating curves are well known. Among the well known flumes belonging to this category are the cut-throat flume, the Leopold-Lagco flume and the Parshall flume.

A cut-throat flume layout proposed by Walker et al [31] is shown in Figure 13. The flume consists of an entrance section with vertical converging walls (3:1) and of an exit section, characterized by the ratio of divergence of 1:6. Typical free-flow and submerged-flow ratings of the flume are shown in Figure 13. According to Walker et al [31], the principal advantages of this flume are basically its flat bottom, simple construction and generalized rating curves, which can be expressed as follows:

$$\text{free flow} \quad Q = C\, h_1^{\,n_1} \qquad \text{submerged flow} \quad Q = \frac{C_1\,(h_1 - h_2)^{n_1}}{(-\log S)^{n_2}} \tag{9}$$

where

Q = flow rate [mgd]

$C = K\,W^{1.025}$ $C_1 = K_1 W^{1.025}$

K, K_1, n_1, n_2 are coefficients (numerical values given in Figure 13)

W = throat width [ft]

h_1, h_2 = upstream and downstream depth, respectively (ft)

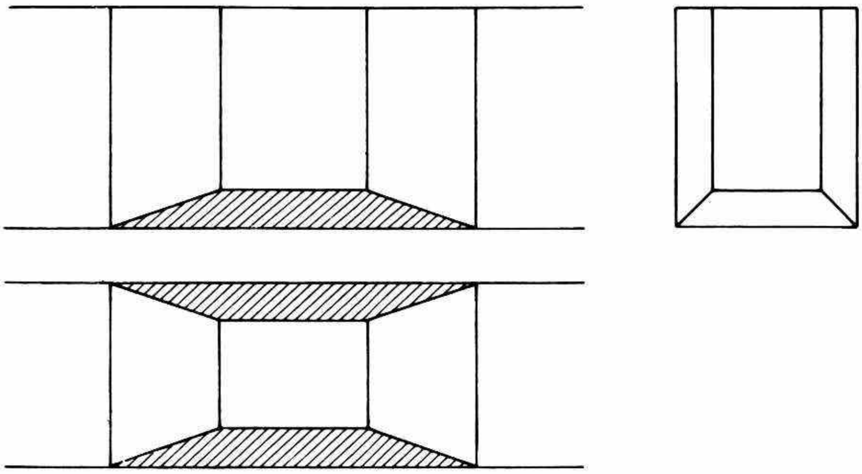
$S = h_1/h_2$ = submergence

The cut-throat flume is applicable to runoff measurements at the outlet.

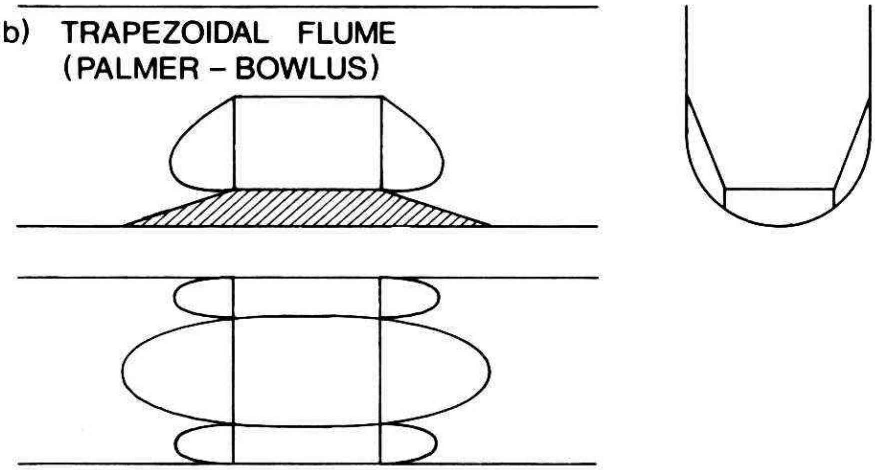
The Parshall flume is well known and has been extensively used in irrigation canals and sewage treatment plants. Details of the flume are shown in Figure 14, together with typical rating curves. As in the previous case, the Parshall flume can be used for runoff measurements at outfalls. Measuring accuracies about ± 5% or better can be expected for flumes constructed exactly according to the flume specifications. Larger errors may occur for very small flows.

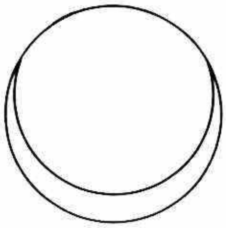
Rating curves of Parshall flumes with the throat section installed level with the bottom of an incoming pipe differ from the standard

a) RECTANGULAR FLUME

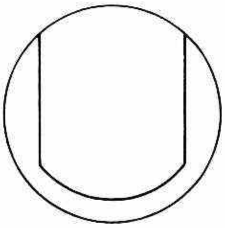


b) TRAPEZOIDAL FLUME
(PALMER – BOWLUS)





c) SEMICIRCULAR
FLUME



d) COMPOSITE
FLUME

e) TWO STAGE COMPOUND FLUME

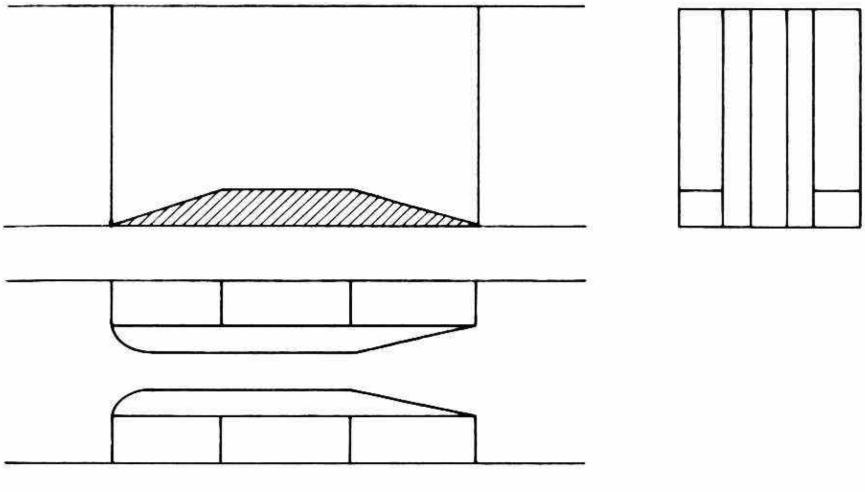


FIG. 12. VARIOUS TYPES OF FLOW MEASURING FLUMES.

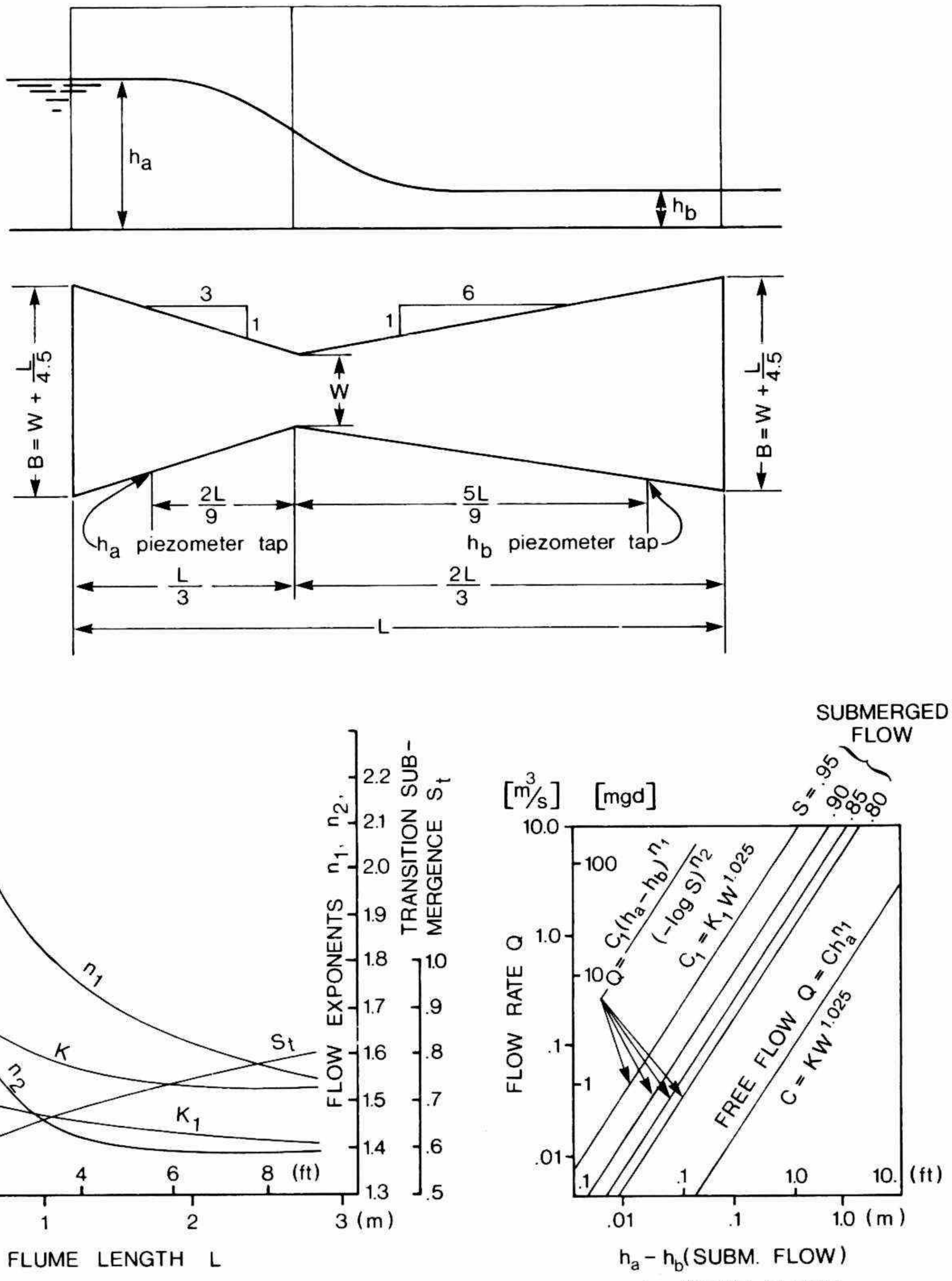


FIG. 13. CHARACTERISTICS OF CUT-THROAT FLOW MEASURING FLUMES.

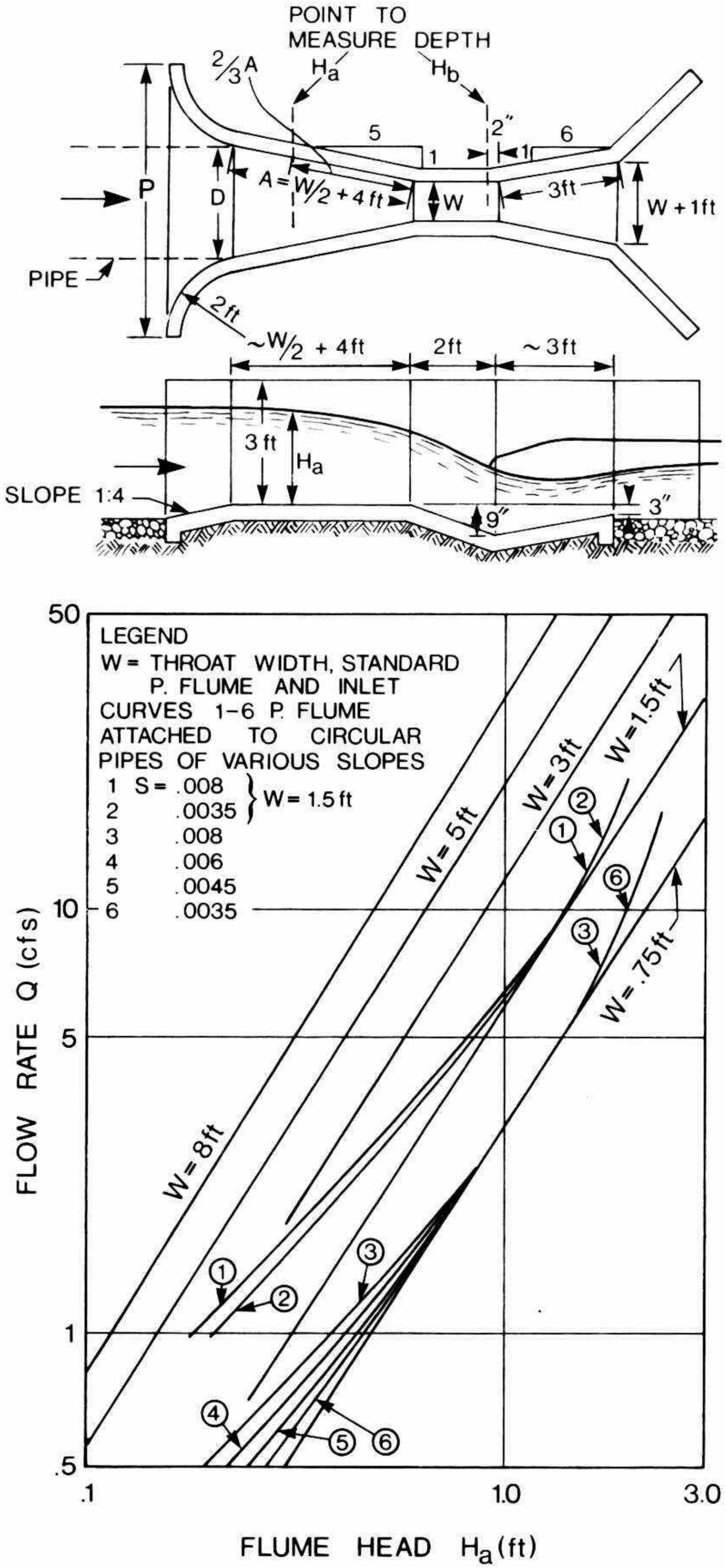


FIG. 14. CHARACTERISTICS OF STANDARD AND MODIFIED* PARSHALL FLUMES

* Attached to a circular pipe.

curves. This is shown in Figure 14 and details can be found in ref. [4].

Leopold-Lagco flumes are manufactured commercially (F.B. Leopold Co. Inc.). The flumes are made of fibreglass and are installed directly in the sewer line (see Figure 15), normally at a standard straight-through manhole. The flumes cause small head losses and can be installed on grades up to 2%. According to the manufacturer, the flume will produce metering heads within 2% of the theoretical rating curve for particular physical conditions of installation.

Leopold-Lagco measuring flumes are made in nominal sizes from 6 to 72 inches, (0.15-1.83 m) with maximum discharge ranging from 0.25 cfs to 118 cfs (0.007 - 3.35 m^3/s), respectively (see Figure 15).

Trapezoidal flumes are very common in sewer flow measurements. Particularly popular is the Palmer-Bowlus flume (Figure 16), which can be installed directly in the sewer line. The flume is available commercially, or can easily be designed and custom made. The cost of such a custom made flume designed for this study was about $100 (size = 30 in. ≃ 0.76 m). After one year of operation in a storm sewer, this flume made of galvanized steel sheet was in perfect shape. The details of the hydraulic design of the Palmer-Bowlus flume are given in ref. [16].

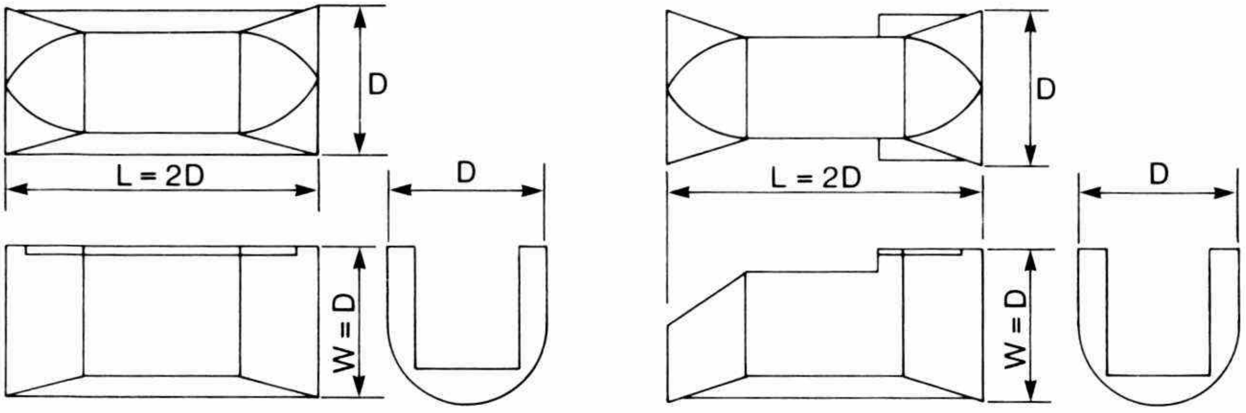
The principal advantages of trapezoidal flumes are smaller reduction of the flow area than in the case of rectangular flumes and also, by selecting the throat width and the slope of sidewall, the flume can be designed to give specific heads at two points within the flow range.

Semicircular flumes (Figure 12c) are not very common. Their main advantage is the wide range of measured flows, because even at low discharge rates, the depth of flow is still large compared with the wetted perimeter.

Compound shapes - a rectangular flume with a semicircular bottom (e.g. the U.S. Geological Survey flume) combines good features of the rectangular and semicircular flumes.

Multiple stage compound flumes extend the operational range of a single-stage flume. An example of a two-stage flumes is shown in Figure 12. The rating curve has to be derived by calibration.

Flume operation and installation. The upstream flow depth (head) is measured at a specific point, exactly defined for the flume under con-



INSERT TYPE

CUTBACK TYPE

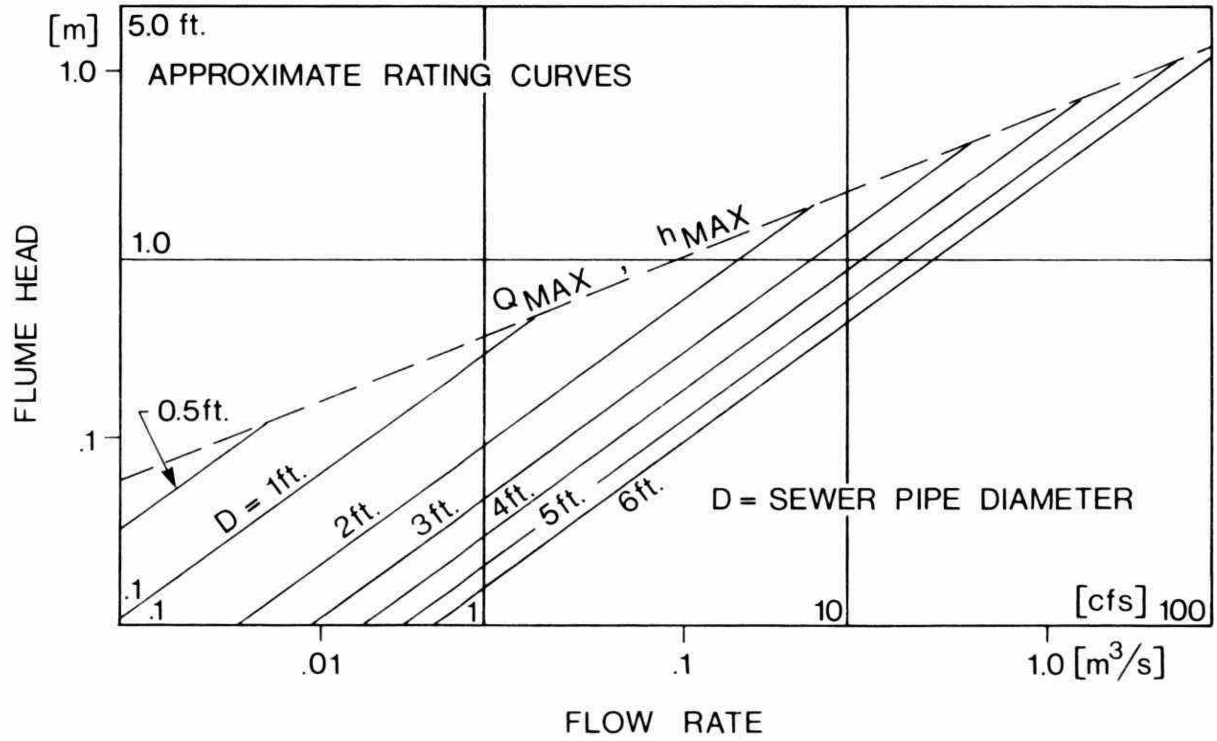
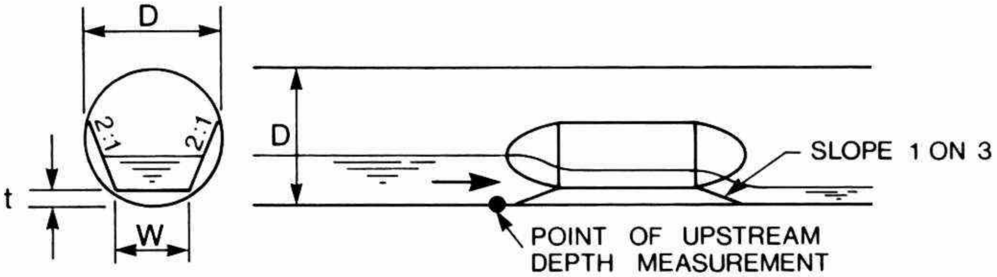


FIG. 15. CHARACTERISTICS OF LEOPOLD-LAGCO FLOW MEASURING FLUME.

a) PALMER - BOWLUS FLUME - FLUME LAYOUT.



FLUME GEOMETRY RECOMMENDED BY LUDWIG (16):
W = 5D/12, t = D/12, SIDE WALL SLOPE 1.5:1 OR STEEPER

b) EXAMPLE OF A RATING CURVE (D = 33", S = .001).
FOR THE METHOD OF DERIVATION OF RATING CURVES FOR SPECIFIC INSTALLATIONS, SEE REFERENCE 16.

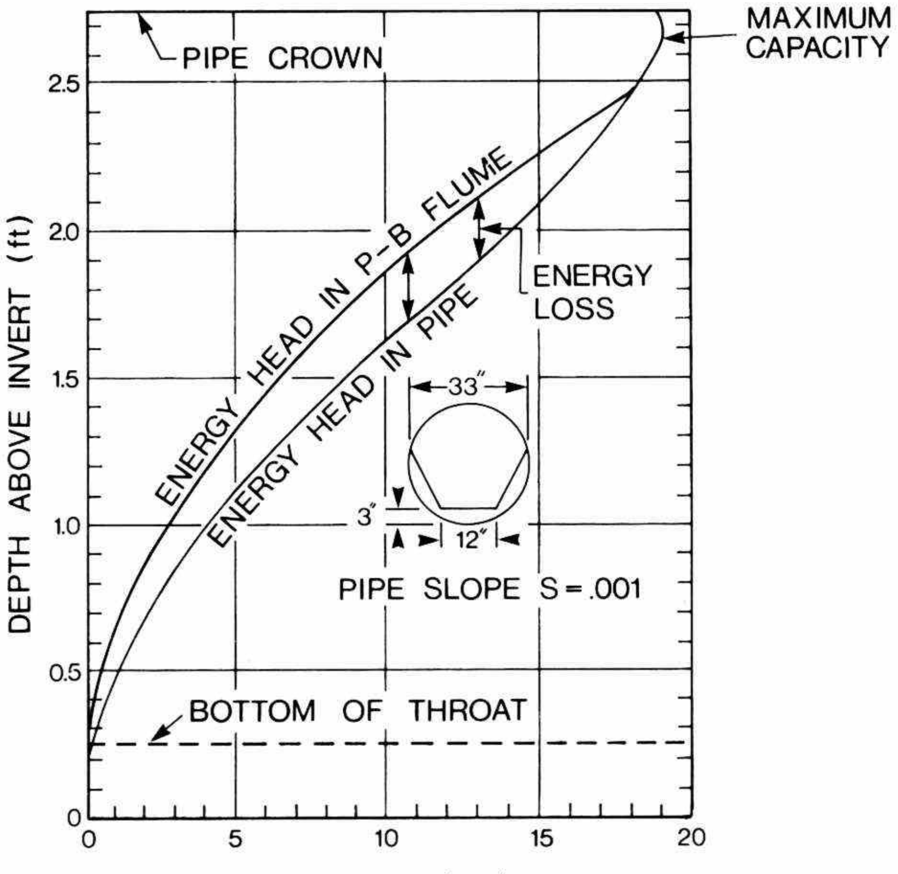


FIG. 16. PALMER - BOWLUS FLOW MEASURING FLUME.

sideration. Sometimes, the flume structure is used to form a stilling well, or the liquid level sensor, usually a capacitance type, is built into the flume wall. Most of the previously discussed liquid level sensors and recorders are applicable for conventional installations. The output signal of level sensors can be usually converted into a flow-proportional signal by means of electronic components or by mechanical cams.

Measuring accuracy - as in the case of weirs, the accuracy of flumes depends on both the accuracy of the flume rating curve and the accuracy of measuring the hydraulic head. For the former accuracy, values in the range 2% to 3% are quoted in the literature, for standard installations. The head is measured typically with an error of ± 1%, which results in the flow measurement error of 1.5% to 2.5% depending on the type of flume. Thus, an overall accuracy of ± 5% of the measured value can be achieved throughout most of the flume operational range, with the exception of very low flows. For very low flows, the error in the rating curve as well as the relative error in the measured head becomes quite significant. This can be somewhat remedied by selecting a proper shape of the flume invert - a semicircular (or similar) invert with relatively large ratios of the depth of flow to the wetted perimeter performs better than flumes with a straight invert.

When selecting the location for a flume installation, the flow characteristics in the adjacent upstream and downstream reaches should be examined. Preferably, the flumes should be installed in sections which do not surcharge frequently, the incoming flow is subcritical and no backwater effects occur. For an incoming supercritical flow, the flume has to create a sufficient constriction of the flow cross-section to cause a hydraulic jump, preferably far upstream from the flume. A hydraulic jump in the proximity of the flume would impair the measurement of the hydraulic head.

The installation of the conventional flumes on supercritical slopes (typically S>2%) should be avoided, since the transition from the shooting to the tranquil flow will frequently result in the sewer pipe surcharging.

The capacity of the downstream reach has to be checked for the occurrence of backwater effects which could create submergency conditions at the flume. Such conditions are tolerable only to some extent.

3.3.8 Other constriction flow meters

The conventional constriction flow meters described in Sections 3.3.6 and 3.3.7 suffer from one common shortcoming - they become inoperational when surcharged. Since every sewer pipe is surcharged at some time, during runoff events of lower-than-design frequency, the inability to measure the pressurized flow may be detrimental for the data collection program. Therefore, some researchers attempted to develop a constriction flow meter which would function for both the free flow and the pressurized flow. Two such meters have been developed - the University of Illinois Sewer Flowmeter [34] and the U.S. Geological Survey Sewer Flowmeter [26]. Both meters are shown in Figure 17.

For free flow, both meters function as Venturi flumes and offer the same reliability and accuracy as such flumes. In fact, the former meter (UI) can be designed for any desired accuracy - the greater the constriction, the better the accuracy.

For pressurized flow, both meters function as Venturi nozzles. Consequently, the pressure before and after the constriction has to be measured to determine the flow rate.

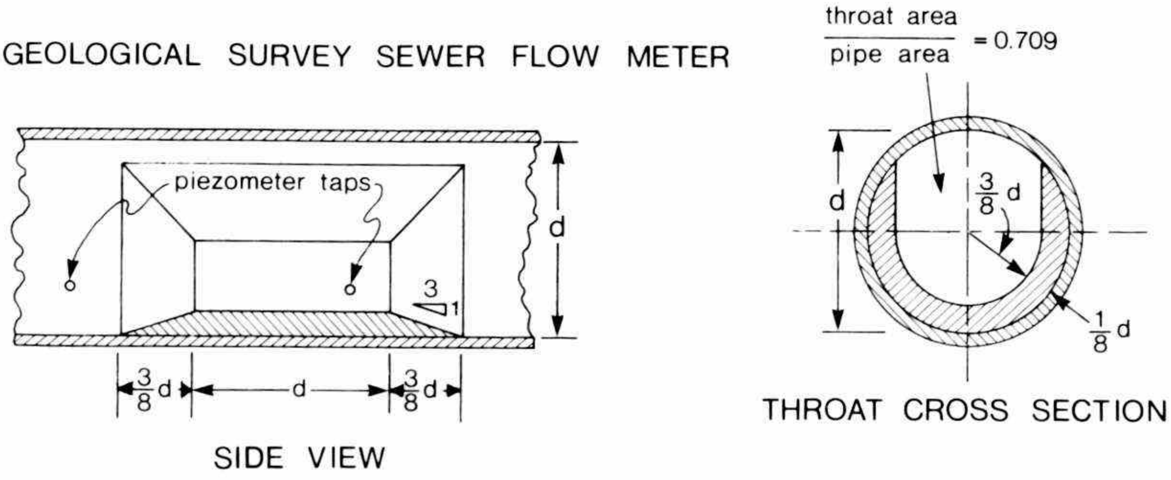
When comparing both flow meters, some preference is given to the U.S. Geological Survey meter, because it has a smoother transition from the free flow to the pressure flow than the University of Illinois meter. This is explained by the fact that the former meter does not obstruct the part of the sewer pipe immediately below the pipe crown.

The U.S. Geological Survey meter has been successfully field tested at two locations. Though the meter is not currently manufactured commercially, the Geological Survey has full documentation for the meter production. The flume is typically made of laminated plastics.

The University of Illinois meter has not been tested in the field so far.

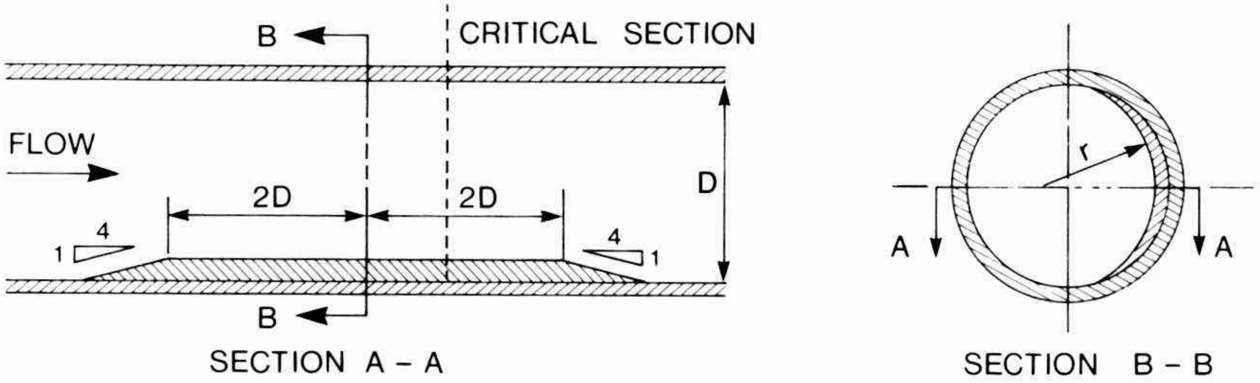
The measurement of head - for free flow, a single head measurement is sufficient. For the pressurized flow, however, the pressure at two points has to be monitored. Pneumatic liquid level sensors (air bubblers) are suitable for such measurements.

US GEOLOGICAL SURVEY SEWER FLOW METER



UNIVERSITY OF ILLINOIS SEWER FLOW METER

A - ASYMMETRICAL



B - SYMMETRICAL

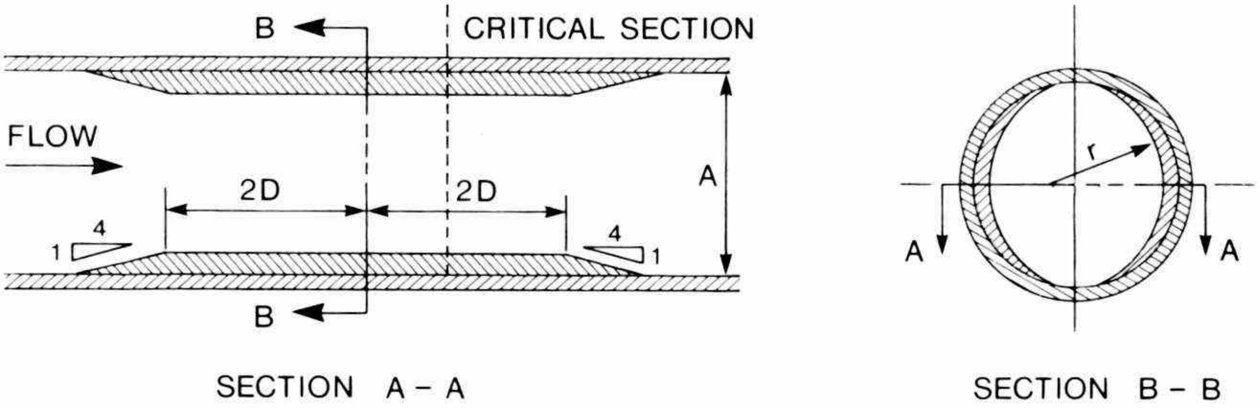


FIG. 17. U.S. GEOLOGICAL SURVEY AND UNIVERSITY OF ILLINOIS FLOW METERS (FOR FREE AND PRESSURE FLOW).

3.3.9 Tracer techniques

Two tracer techniques are commonly used for flow measurements - the time of travel method and the tracer dilution method. The former method was briefly described in Section 3.2; a description of the latter technique follows.

If a small flow of q containing tracer at concentration C_o is added to an unknown flow Q with the tracer concentration C_1, then from the tracer mass balance, it follows that

$$Q = \frac{q(C_o - C_2)}{C_2 - C_1} \tag{10}$$

where C_2 is the tracer concentration at a downstream flow monitoring station. In most cases, Equation (10) can be further simplifed by considering

$C_2 << C_o$ $\qquad$ $C_1 << C_2$

The simplified equation then reads

$$Q = q \frac{C_o}{C_2} \tag{11}$$

Details of the technique are described in ref. [17, 22].

The tracer dilution technique was automated and tested by the study team. A tracer feed pump was automatically activated during the periods of runoff. Runoff samples collected automatically at a downstream station were analyzed in the laboratory for the tracer concentration C_2. The flow rates could then be determined from Equation (11). The calculated flow rates were then compared with readings of a calibrated weir (see Figure 18). It was found that the method can yield flow measurement accuracy of about 4% - 5%, if utmost care is exercised in the measurements. It is particularly important to ensure full mixing of the tracer with the measured flow.

The technique suffers from some shortcomings - only discrete flow measurements are taken and instrument malfunctions, particularly in the case of an automatic sampler, are quite probable. Consequently, the

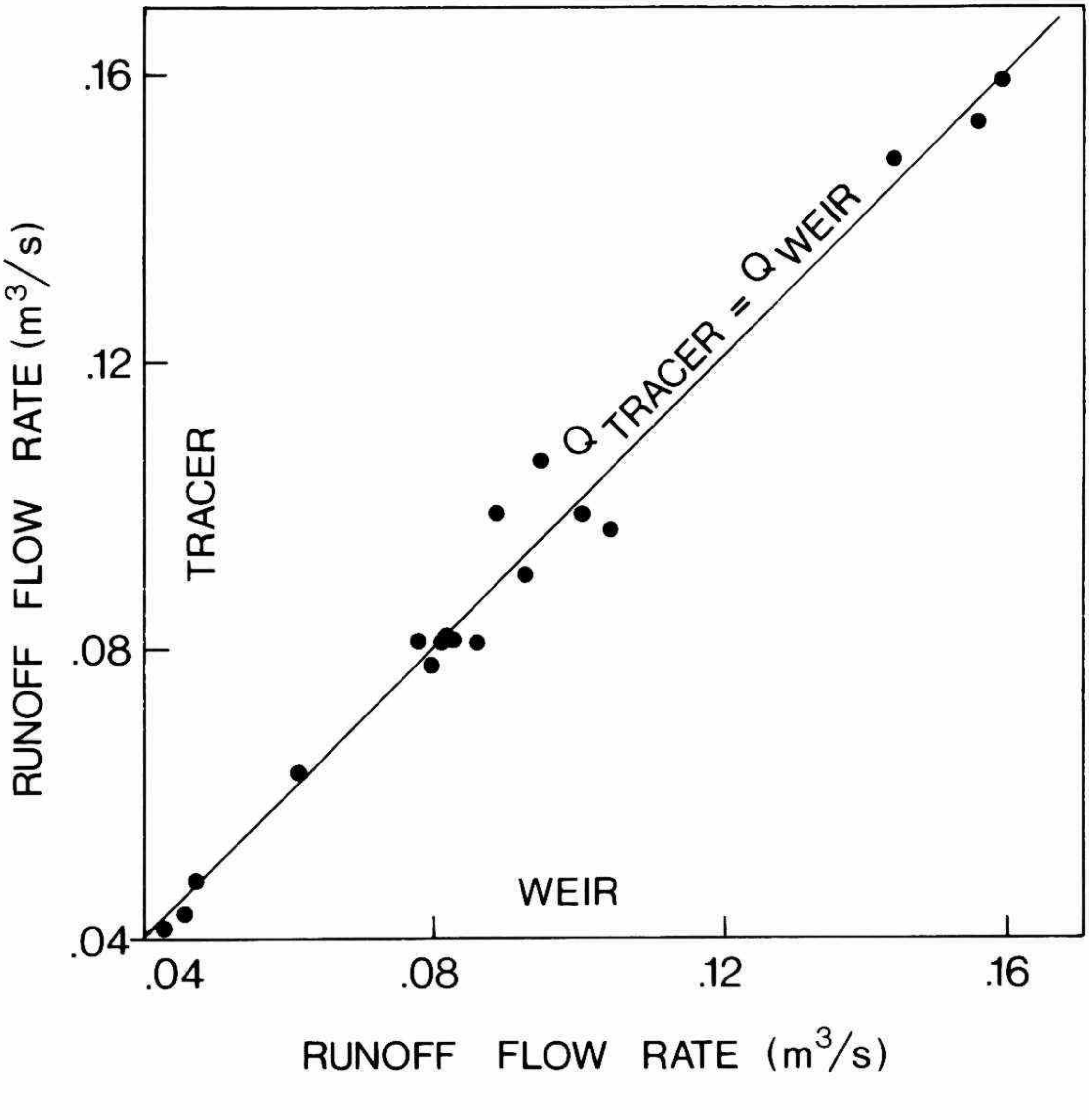


FIG. 18. COMPARISON OF RUNOFF FLOW RATES MEASURED BY THE TRACER DILUTION METHOD WITH WEIR MEASUREMENTS.

method has only some limited practical application, such as for in-situ calibration of constriction flow meters.

3.3.10 Recently studied or developed techniques

Some modern flow measuring techniques were recently tested for a possible application in sewer studies. Among these, one could name [11] the vibratory mass flow meter, the thermal wave flow meter, the steam pulse flow meter, the "passive" flow meter, the rotameter-type flow meter and hot wire anemometers. Though some of these instruments show good promise, none of them was found so far feasible for application in sewer studies.

3.3.11 Combined techniques

Additional flow measuring techniques can be devised by combining two or more previously described techniques. One such a possibility was attempted in a related study: using a conventional constriction flow meter for the free flow and the tracer dilution technique when the meter was surcharged [17]. Though such a system could be possibly used under some circumstances, the probability of losing data is fairly high because of the large number of instruments involved.

3.4 Overview of Flow Measurement Techniques

The findings of this chapter can be summarized as follows:

Whenever feasible, runoff flows should be measured at the outfall, outside the sewer system. Conventional constriction flow meters, such as weirs or flumes, can be used. Weirs are inexpensive, but may block the transport of solids. Flumes are more expensive, but allow the passage of solids and cause a smaller energy loss than weirs.

If it is necessary to measure inside the sewer system, and the sewer pipe is not frequently surcharged, inexpensive trapezoidal weirs without the bottom part, or flumes, such as Palmer-Bowlus, are applicable. For frequently surcharged pipes, a dual free/pressurized flow meter such as the U.S. Geological Survey Sewer Flow meter should be used.

A brief overview of the discussed flow measurement methods is shown in Table 3.

TABLE 3. OVERVIEW OF SEWER FLOW MEASUREMENT TECHNIQUES

Technique	Free Flow	Free & Pressure Flow	Applicable			Estimated Accuracy	Cost Range	Recommended
			At Outfall	Man-Hole	Sewer Pipe			
Depth Meas.only	X	X[1]	X	X		20%	L[2]	No
Depth & point velocity	X		X	X		5%	H[4]	Yes
Specific energy	X			X		20%	L	No
Depth & chord velocity	X	X	X	X	X	3%?	H	Yes
Weirs -								
rectangular	X		X			5%	L	Yes
V-Notch	X		X			5%	L	Yes
Trapezoidal	X		X	X	X	5%	L	Yes
Vertical slot	X		X	X	X	5%	L	Yes
Flumes -								
Leopold-Lagco	X		X	X		5%	M[3]	Yes
Parshall	X		X			5%	M	Yes
Palmer-Bowlus	X		X	X	X	5%	M	Yes
U.S.G.S.	X	X	X		X	5%	M-H	Yes
U. of Ill.	X	X	X		X	5%	M-H	Yes
Tracers	X	X		X		5%	M	No

[1] Measuring pressure drop between two manholes

[2] Low cost

[3] Medium cost

[4] High cost

4 WATER QUALITY SAMPLING

The quality of storm water and combined sewage is commonly determined by the laboratory analysis of samples collected in the field. The uncertainty of the quality data then depends on the number and representativeness of collected samples and the uncertainty inherent in the laboratory analysis. Generally speaking, the first two factors, the number and representativeness of collected samples, are more important than the last one, and only these two aspects will be discussed in this section.

Representative sampling of storm and combined sewage is an extremely difficult task, since the sampled medium is nonhomogeneous and its composition varies in time and space. Furthermore, the sampling is typically done in a very adverse environment of sewers, with limited accessibility, space limitations and lack of AC power. Unfortunately, none of the commercial samplers was specifically designed for runoff studies, and consequently, none of them was found particularly suitable for such purpose [23, 24].

In the light of these facts, the following discussion should be looked upon as only a guideline for reducing sampling errors, since no universal, foolproof sampling systems are available. The recommendations given are made on the basis of field experience as well as on the basis of a literature survey.

For the descriptions of available automatic samplers, the reader is referred to an assessment of automatic sewer flow samplers by Shelley and Kirkpatrick [24]. This assessment was based on a study sponsored by the U.S. Environmental Protection Agency and covers the makes of samplers available in 1972. For some recently introduced samplers, the reader should contact sampler manufacturers.

4.1 Sampling Techniques

In practice, the following sampling techniques are used:

Composite sampling - simple composition
flow-weighted composition
pollutant mass-flow-weighted composition
Sequential grab sampling
Sequential composite sampling

The selection of a sampling technique depends on the objectives of a particular runoff quality study. The objectives usually are to estimate the total pollutant yield from a runoff event, and/or to estimate the pollutant concentration variation during the event. The latter objective is more frequent in runoff studies, particularly if selective retention and treatment of storm water and combined sewage are considered.

4.1.1 Composite sampling

Composite sampling involves lumping together all samples collected during a runoff event. The composite sample then represents an average pollutant concentration for the event. The main advantage of the composite technique is the low cost of quality analysis, since only one sample per runoff event has to be analyzed.

Simple composite sample (non-weighted). In this sampling technique, constant aliquots of storm water are withdrawn at regular time intervals and collected in one container to constitute the composite sample. The technique is rather inexpensive and the least sophisticated samplers and flow recorders may be used.

The simple composite sample is not acceptable for urban runoff studies, because it significantly underestimates the total pollutant yields. The reason for this underestimation is that the high concentrations and flow rates in the initial runoff period are assigned the same statistical weight in the sample composition as the low concentrations and flow rates in the latter part of the runoff. The data in Table 4 indicate that this underestimation could be in the order of 30% of the estimated actual value. The error is little affected by the frequency of aliquot withdrawals.

Flow-weighted composite sample. The flow-weighted sample composition requires more sophisticated and more expensive equipment than the simple composition. The flow-weighted composition is done either automatically or manually. Two automatic techniques are available. In the first one, a constant fraction of the flow is collected continuously. In the second automatic technique, samples of constant volume are withdrawn at irregular time intervals, based on a preselected constant quantity of storm water passing through the metering station.

TABLE 4. APPLICATION OF COMPOSITE SAMPLING TECHNIQUES TO RUNOFF QUALITY DATA. (Runoff quality data after reference 5)

	Sample number	Time (min)	Flow rate (m^3/s)	COD (mg/l)	BOD (mg/l)	Total solids (mg/l)	Susp. solids (mg/l)	Settl. solids (mg/l)
	1	0	0.00	430	13	14600	9600	6756
	2	5	4.14	400	15	12560	11200	7640
	3	10	4.73	280	11	6638	6050	3330
	4	15	3.65	170	16	5830	5520	2660
	5	20	3.01	310	15	10002	9020	6528
	6	25	2.73	300	15	10632	10010	6906
	7	30	3.65	370	5	10242	9170	5702
	8	35	0.97	240	8	8676	8150	6662
	9	40	0.79	230	13	7196	5560	2913
	10	45	0.64	210	15	6092	5900	2332
	11	50	0.50	210	16	4898	4620	2530
	12	55	0.38	230	4	4598	3920	3616
	13	60	0.29	150	15	3908	3140	2792
	14	65	0.30	135	16	3403	2650	1904
	15	70	0.32	120	17	2898	2160	1016
	16	75	0.28	130	15	2604	2040	1026
	17	80	0.24	140	14	2310	1920	1036
	18	85	0.23	130	14	1990	1470	698
	19	90	0.23	120	14	1670	1020	360
	20	95	0.26	89	13	1562	1090	442
	21	100	0.30	58	12	1454	1160	524
Actual total yield (kg)				2377	97	72202	63348	41326
Simple composite sampling (5 min. Interval) - total pollutant yields in percent of actual yields				76%	113%	69%	67%	66%
Flow-weighted composite sampling -total yields in percent of actual yields. Sampling intervals: a/5 min. b/10 min. c/20 min.			a	100%	108%	100%	100%	100%
			b	106%	99%	101%	97%	95%
			c	108%	121%	115%	103%	109%

The former automatic technique is rather impractical in urban runoff studies because of the large flows involved. The latter technique requires the installation of a flow meter with a flow integrator to activate the sampler.

The manual flow-weighted sample composition is achieved by proportioning the volume of individual sequential grab samples relative to the flow which passed between the collection of two consecutive samples. The proportioning is done after the runoff event using the flow record.

The manual flow-weighted sample composition was applied to the runoff quality data in Table 4. The results show that the method gives good estimates of the total pollutant yield, provided the samples are withdrawn at a rate of one sample every 5 to 10 minutes. As the sampling interval increases, the error in the calculated yield of pollutant increases too, because the variation in pollutant concentration between the sampling events is neglected. At closer time intervals, the variation in concentration become negligible. The results in Table 4 show that, for average sampling intervals of 5-10 minutes, the error in the calculated yields is less than 10%.

In automatic flow-weighting, the sampling interval varies. The interval could be as short as one to two minutes during the peak flows. The setting for the flow volume passing between the two consecutive samples should be done in such a way that the average sampling interval during the runoff event is not greater than 10 minutes. This requires some knowledge of the volume and duration of runoff in the studied area.

Pollutant mass-flow-weighted composite sample. This composition technique requires continuous approximate monitoring of the quality parameter under study, or of a parameter which can be related to the one being studied. In the latter instance, for example, the monitoring of suspended solids was approximated by monitoring the turbidity [20].

The output from the quality probe, pollutant concentration, is multiplied by the flow rate to yield the pollutant mass flow. The mass flow is then integrated and samples are collected at preselected constant increments of the cumulative pollutant mass flow. The laboratory analysis of the composite sample is believed to give a more accurate and reliable result than the direct processing of the quality probe output.

The pollutant mass-flow-weighted sample composition is the best composition technique, because it takes into account not only the flow rate variation but the pollutant concentration variation as well. The application of the technique in urban runoff studies is rather limited owing to the difficulties with continuous monitoring of water quality parameters.

As stated before, composite sampling will not be adequate when the time variation of pollutant concentrations is of interest. Under those circumstances, the use of sequential grab or sequential composite sampling is necessary.

4.1.2 Sequential grab sampling

In sequential sampling, discrete grab samples are collected at constant or variable time intervals. The sample collection has to be done automatically, because in the case of manual grab sampling, it is practically impossible to dispatch the field personnel in time to start sampling at the very beginning of a runoff event.

A practical objective in studies of pollutant concentration variation is to obtain an acceptable accuracy at minimal costs. This objective may be met only by applying experimental design techniques. For urban runoff quality studies, the main problem in designing an effective sampling program is to determine the least number of samples required to accurately delineate the variation in concentration. Careful consideration of the number of samples is warranted because the cost of detailed analyses of storm water samples usually exceeds $100 per sample. Significant savings may be realized by the application of experimental design to runoff quality studies.

The application of experimental design techniques, in this case of the prediction analysis, requires the adoption of an empirical model of the studied phenomena. Such an empirical model, based either on the experience from other studies or on the results of preliminary observations, is used to guide the data collection. In the initial stages of a study, a crude model is sufficient. At the present level of knowledge, however, the formulation of such a model may not be always feasible. Also, various quality parameters may require various time-distribution models which further complicate this approach. An example of the experimental design for sequential sampling is given in the Appendix (after ref. [18]).

In the currently common approach, the constant sampling interval is selected on the basis of experience and the size of the studied area. A review of 10 urban runoff studies (i.e. storm water runoff as well as combined sewer overflows) yielded the sampling intervals shown in Table 5 and Figure 19.

TABLE 5. SAMPLING INTERVALS IN URBAN RUNOFF STUDIES

Watershed Size (Acres)	Watershed Size (ha)	Sampling Interval (Minutes)	24 Sample Cycle Duration (Hours)
10	4	5	2
50	20	5-7.5	2-3
100	40	5-10	2-4
500	202	10-15	4-6
1000	455	10-15	4-6
2000	809	15	6
3000	1214	20	8
5000	2023	25-30	10-12

Other factors to be considered in the selection of a sampling interval is the precipitation time-distribution and the watershed hydrologic response. These two factors influence the runoff flow rates to which the storm water quality seems to be related [30]. Consequently, high intensity and low duration summer storms on fast responding watersheds will call for shorter sampling intervals and vice versa.

The first sample should be collected as close to the beginning of runoff as feasible. This can be achieved by activating the sampler by the first impulse from the precipitation sensor, or better, by the rise of the water level in the sewer by a preselected increment.

The latter technique was used by the study team on two installations. Some electronic liquid level sensors (e.g. capacitance probes, Manning Dipper, ultrasonic probes, etc.) can be equipped with alarm relays and these are then used to close the power supply circuit of the sampler when sewage reaches the selected level. In case of sensors without alarms,

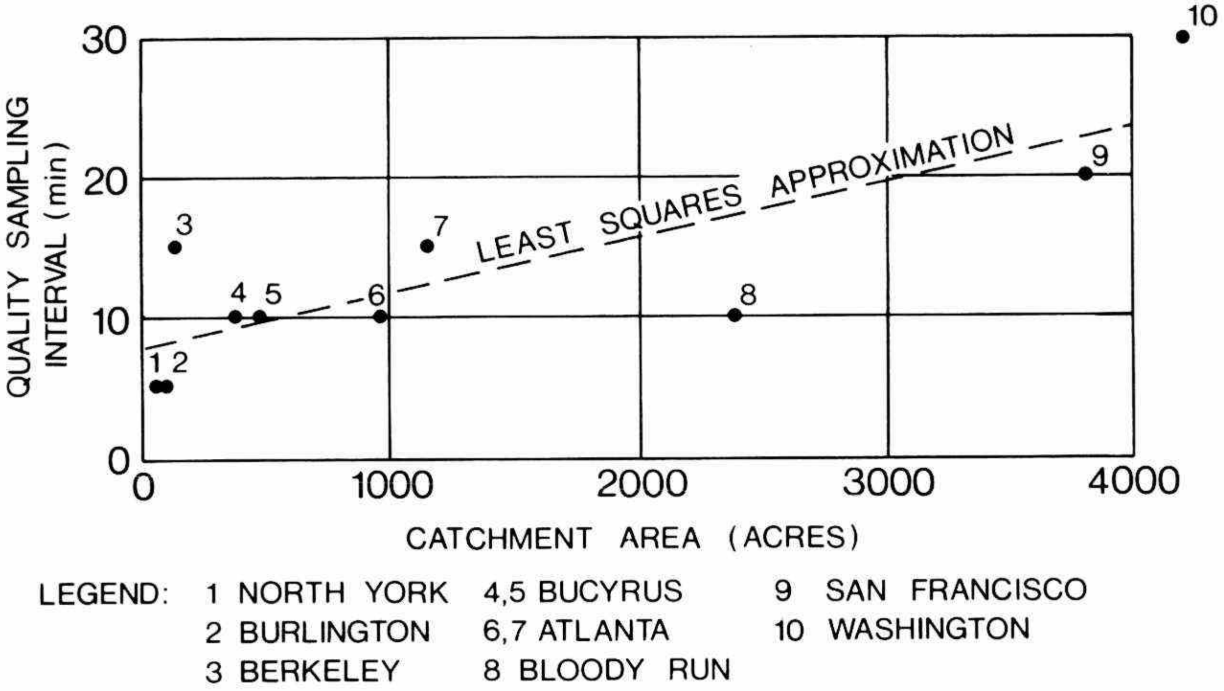


FIG. 19. QUALITY SAMPLING INTERVAL IN RUNOFF STUDIES.

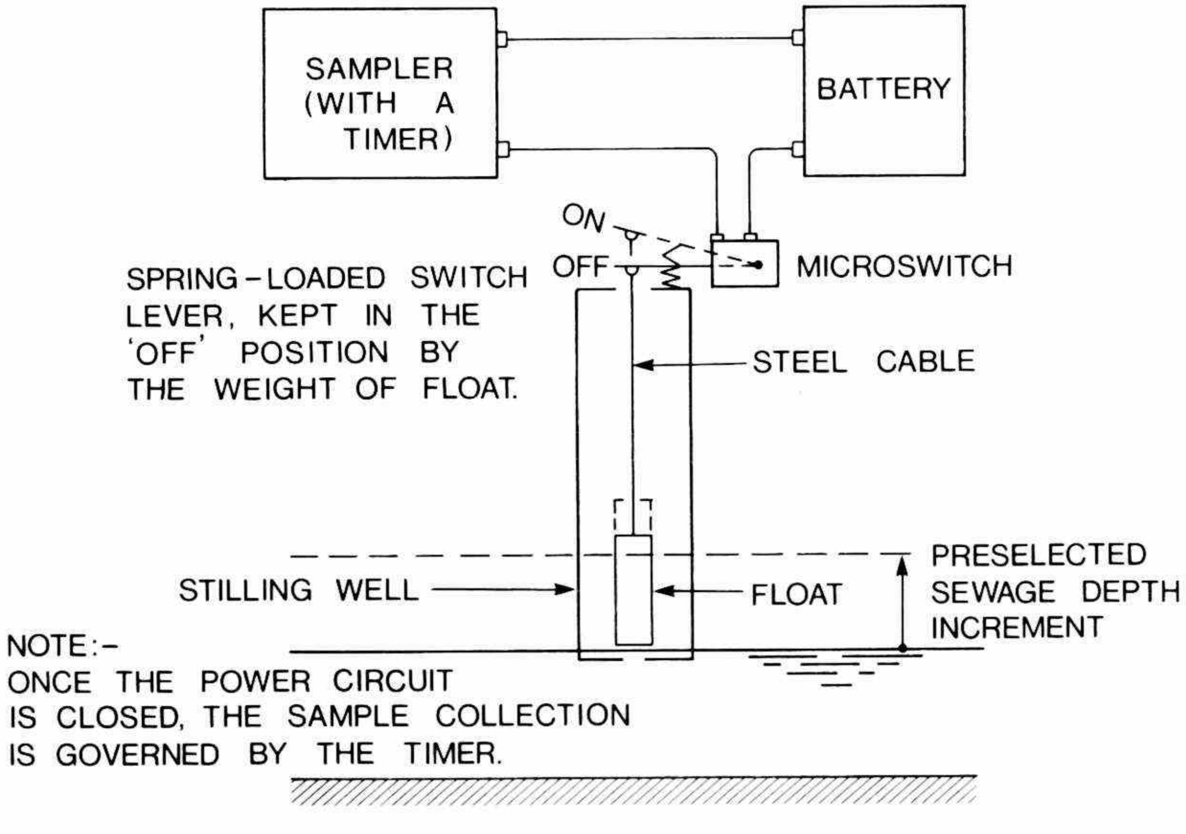

SAMPLER (WITH A TIMER)
BATTERY
ON
OFF
MICROSWITCH
SPRING-LOADED SWITCH LEVER, KEPT IN THE 'OFF' POSITION BY THE WEIGHT OF FLOAT.
STEEL CABLE
STILLING WELL
FLOAT
PRESELECTED SEWAGE DEPTH INCREMENT
NOTE:- ONCE THE POWER CIRCUIT IS CLOSED, THE SAMPLE COLLECTION IS GOVERNED BY THE TIMER.

FIG. 20. SAMPLER ACTIVATION EFFECTED BY THE RISE OF SEWAGE LEVEL.

microswitches were used to perform the same function. The microswitch can be activated by a small auxiliary float installed at the monitoring cross-section (see Figure 20) or in case of float liquid level sensors, by the main float.

In the case of the timer-controlled samplers, the first impulse switches the timer on, and the sample collection is governed by the timer at regular time intervals. Such an arrangement is fully satisfactory.

In some installations, sample collection is governed by the flow meter. Sequential samples are collected after a preselected volume of water passed through the monitoring station. Such an instrumentation system is more expensive than the former one.

4.1.3 Sequential composite sampling

In this technique, sequential samples are taken, but each of these is a composition of several subsamples. Such a technique represents a compromise between the composite and sequential grab sampling and is not commonly used in runoff studies.

4.2 Samples

Sample size and preservation are two important considerations when selecting an automatic sampler. A discussion of both follows.

4.2.1 Sample size

The selection of the sample size should be based on the volume of sewage required for the intended chemical analyses. The list of parameters usually investigated in runoff studies is shown in Table 6. The required volumes for the individual analytical tests vary according to the procedures used and should be established by the analytical laboratory. The sample size is then the sum of all required subvolumes.

Rather popular, lightweight, portable samplers collect typically only 500 ml (about 18 fluid ounces) samples. Such a volume is hardly sufficient even for the most common group of analytical tests - BOD, COD, suspended solids, settleable solids, total phosphorus and total nitrogen. To provide sufficient aliquots for the above tests, eventually for some others (e.g. heavy metals, and chlorides - in winter), it is necessary to

TABLE 6. WATER QUALITY PARAMETERS INVESTIGATED IN URBAN RUNOFF STUDIES.

Parameter	Frequency of use	
	Common	Less Common
Biochemical Oxygen Demand	X	
Chemical Oxygen Demand	X	
Total Organic Carbon		X
Total Solids	X	
Suspended Solids	X	
Dissolved Solids	X	
Volatile Suspended Solids	X	
Volatile Dissolved Solids		X
Total Organic Kjeldahl Nitrogen	X	
Nitrogen - Ammonia		X
Nitrate and Nitrite	X	
Phosphorus - Total P	X	
Orthophosphate Hydrolyzable	X	
Orthophosphate Soluble	X	
Oil and Grease		X
Phenols		X
Chloride	X	
Organic Chlorine		X
Mercury		X
Lead	X	
Zinc		X
Total Coliform	X	
Fecal Coliform	X	
Fecal Streptococcus		X

collect at least 1000 ml (35 fluid ounces) samples. Though commercial samplers collecting samples of this size are available, they are more or less designed for semi-permanent installations and some of them cannot be installed in manholes because of space limitations.

Custom designed and made samplers offer a better choice of the sample sizes. Samples as large as 2000 ml (70 fluid ounces) are used. For the description of a number of custom designed samplers, the reader is referred to ref. [24].

4.2.2 Sample preservation

The analytical laboratory should be contacted regarding the sample preservation before the delivery to the laboratory. Commonly, such preservation consists in cooling the samples to about $4^{o}C$. This can be done by using a heavy-weight sampler with a refrigeration unit, or in case of some portable units, a cavity to be filled with ice is provided. In some custom sampling systems, a non-refrigerating type of a sampler or only the bottle tray are placed inside a household refrigerator. If none of the above measures are taken, an early removal of samples from the sampler should be ensured, within several hours after the runoff event. The samples should then be transferred to the laboratory cold storage.

Sample bottles - virtually all commercial samplers use plastic or glass bottles which have to be washed after each use. This time-consuming chore is eliminated when using disposable containers as done in the case of some custom designed samplers [24].

4.3 Practical Aspects of Sampling Installations in Urban Runoff Studies

The discussion in the preceding chapter assumed that the collected samples are truly representative for the storm water quality. To achieve this sample representativeness, systematic errors in the sampling technique should be avoided. The main sources of systematic errors in the sampling in urban runoff studies are as follows:

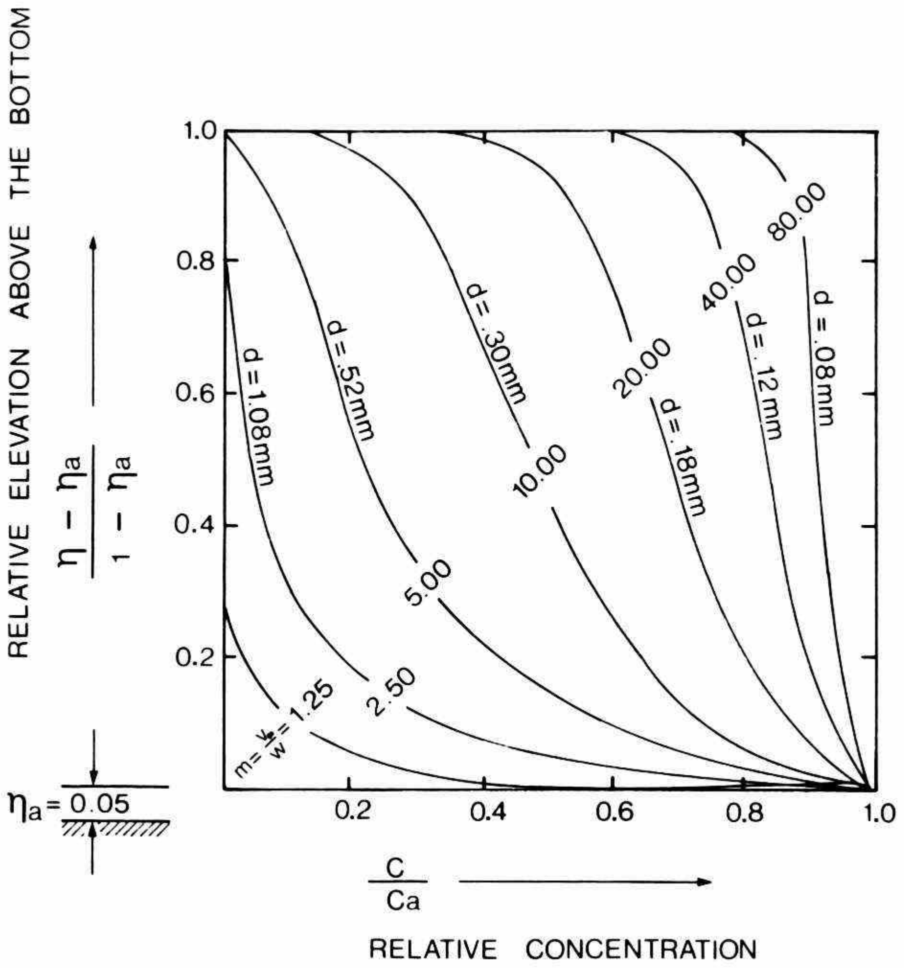
a) The depth of sample withdrawal in a non-homogeneous media.
b) Capability of the sampler to collect solids.
c) Sample cross-contamination.
d) Lack of synchronization between the flow recording and the sampling.

4.3.1 The depth of sample withdrawal in a non-homogeneous media

The sample withdrawal depth is important for those flows where the solids concentration distribution along a vertical is non-uniform. The concentration distribution depends on the flow characteristics (shear velocity) and the characteristics of solid particles (fall velocity). Such a relationship is plotted in Figure 21 (after ref. [12]). As an example, a shear velocity of 0.4 m/s was assumed, which corresponds to a 4 ft concrete pipe flowing nearly full on a 1% slope, and the concentration distributions were identified by the particle sizes. An acceptably uniform concentration distribution was obtained in this case only for sand-like particles smaller than 0.12 mm. Larger particles which still may contain a significant portion of the pollutional load have non-uniform concentration distributions. Thus the measured concentrations of solids and solids-bound pollutants will be affected by the depth at which the sample was withdrawn.

A highly non-uniform distribution of solids and BOD with depth was also found in field observations. Four sets of sewage samples were collected in a straight reach of a 4 ft sanitary sewer during wet weather. Each set consisted of six samples collected simultaneously at various levels above the pipe invert. The samples were analyzed for suspended solids and BOD_5 concentrations. The results are shown in Figure 22 and indicate a sharp gradient in the solids and BOD concentrations in the vertical plane. In both cases, the mean concentration, defined as the pollutant mass flow rate divided by the flow rate, occurred at about the midpoint of the flow depth. Thus samples collected in the upper half of the flow would yield below-average concentrations and samples collected in the lower part of the flow would yield above-average concentrations. For other flow conditions and pollutional loads, the concentration distributions are likely to be different.

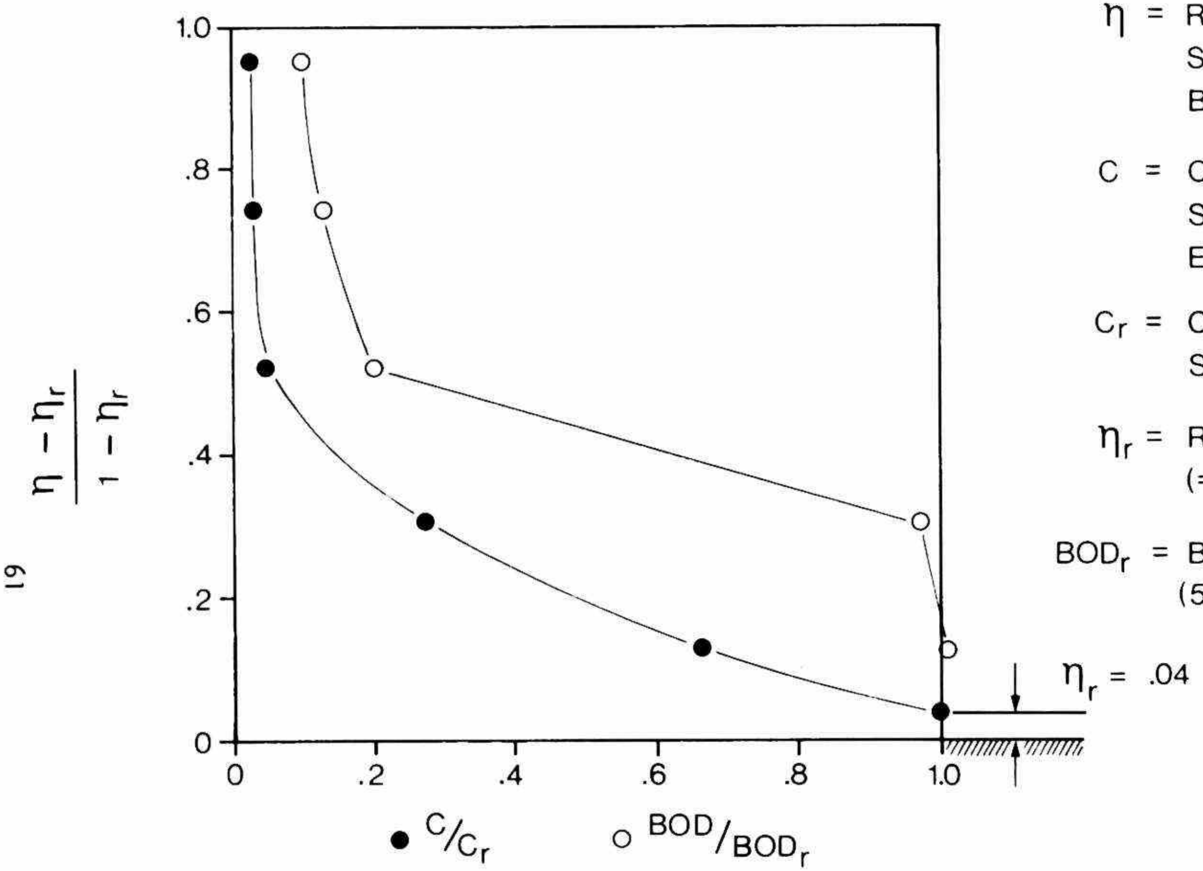
Since it is practically impossible to account for the sewage density stratification in a sampling operation by means of hardware, a partial remedy may be achieved by destroying the stratification by means of mixing and turbulence. As a stopgap, it is recommended to locate the sampler intake at a cross-section where the flow is very turbulent, e.g. close to the lateral inflows or vertical drops.



LEGEND

η	RELATIVE ELEVATION ABOVE THE CHANNEL BOTTOM (= ELEVATION ABOVE THE BOTTOM / DEPTH OF FLOW)
C	VOLUMETRIC CONCENTRATION OF SUSPENDED SOLIDS MEASURED AT ELEVATION η
η_a	REFERENCE RELATIVE ELEVATION
Ca	VOLUMETRIC CONCENTRATION OF SUSPENDED SOLIDS MEASURED AT ELEVATION η
V_*	SHEAR VELOCITY
W	FALL VELOCITY OF SEDIMENT PARTICLES
d	SIZE OF SAND-LIKE PARTICLES CORRESPONDING TO THE m VALUES FOR $V_* = .4$m (THIS VELOCITY CORRESPONDS TO A 4ft CONCRETE PIPE FLOWING NEARLY FULL ON A 1% SLOPE

FIG. 21 THEORETICAL CONCENTRATION DISTRIBUTION WITH DEPTH (AFTER REF.12)



η = RELATIVE ELEVATION ABOVE THE SEWER BOTTOM (EL. ABOVE BOTTOM / DEPTH OF FLOW)

C = CONCENTRATION OF SUSPENDED SOLIDS (mg/l) MEASURED AT ELEVATION η

C_r = CONCENTRATION OF SUSPENDED SOLIDS MEASURED AT η_r

η_r = REFERENCE RELATIVE ELEVATION (= .04)

BOD_r = BIOCHEMICAL OXYGEN DEMAND (5 DAY) AT η_r

FIG. 22 DISTRIBUTION OF BOD AND SUSPENDED SOLIDS CONCENTRATION WITH DEPTH (THE RESULT REPRESENTS AN AVERAGE OF 4 SETS OF MEASUREMENTS IN A SANITARY SEWER; DEPTH OF FLOW h = .61m)

4.3.2 Capability of the sampler to collect solids

The capability of a sampling installation to collect solids is particularly important and should be evaluated in those studies of urban runoff in which the solids and solids-bound pollutants represent a significant portion of the total pollutant yield.

According to ref. [35], most of the solids which eventually end up in the runoff contain various pollutants in significant concentrations. Some data from ref. [35] are shown in Table 7 and indicate the pollutant concentrations found in the street surface contaminants of various sizes.

TABLE 7. FRACTION OF POLLUTANT ASSOCIATED WITH EACH PARTICLE SIZE RANGE FOR STREET SURFACE CONTAMINANTS (% by weight) - after reference [35].

	particle size (μ)					
	> 2000	840-2000	246-840	104-246	43-104	< 43
Total solids	24.4	7.6	24.6	27.8	9.7	5.9
Volatile solids	11.0	17.4	12.0	16.1	17.9	25.6
BOD_5	7.4	20.1	15.7	15.2	17.3	24.3
COD	2.4	4.5	13.0	12.4	45.0	22.7
Kjeldahl Nitrogen	9.9	11.6	20.0	20.2	19.6	18.7
Nitrates	8.6	6.5	7.9	16.7	28.4	31.9
Phosphates	0.0	0.9	6.9	6.4	29.6	56.2
Total heavy metals	16.3	17.5	14.9	23.5	27.8	
Total pesticides	0.0	16.0	26.5	25.8	31.7	

An installation with a limited capability to collect solids may lead to an erroneous estimate of not only solids yields, but of other pollutant yields as well. The data in Table 7 should be used only as a general guide, because they apply to the dry street surface contaminants of which specific gravity is not known. The particle size might be reduced by attrition during the transport to the sewer inlet and through the sewer pipe. Also the collection and transport of particles having a smaller specific gravity than sand is more easily achieved.

The efficiency of the solids collection by a sampler is affected by the orientation of the intake and by the velocities in the intake nozzle and line.

The orientation of the sampler intake with regard to the flow direction has a definite effect on the concentration of solids in the collected samples. This effect was studied in the laboratory [14] using sand particles. Some data from ref. [14] are replotted in Figure 23. The data show that unless the intake is oriented axially, pointing upstream, the solids concentration in the sample is always smaller than that in the sampled flow. In the studied case (sand, 0.15 mm), the bottom intake underestimated the sample concentrations constantly by about 14% over the whole range of intake velocities. A laterally oriented (90°) side intake underestimated the sample concentration by 15 to 55% depending on the ratio of the intake to flow velocity.

The axial intake pointing upstream gives solids concentrations which depend on the ratio of the sampling (intake) velocity to the flow velocity. This dependency was significant only for large particles (sand, 0.45 mm); it practically disappeared in case of small particles (sand 0.06 mm).

The sewage velocity varies during runoff events, while the sampling velocity remains virtually unchanged. Therefore, the ratio of sampling velocity to the flow velocity will vary and the sampler efficiency of the solids collection will vary as well. The only intake which is unaffected by the above velocity ratio is the bottom intake. It could be used in cases where a false floor or a "hump" is installed in the existing sewer system.

In field studies of urban runoff, the sampler intake is typically suspended from the top or oriented axially but pointing downstream. These intake arrangements are usually necessary to prevent the clogging of the intake. Solids concentrations in the samples collected in these installations will be underestimated according to the previous discussion.

Another factor which affects the solids collection by a sampler is the intake line velocity. The intake line velocity differs from the sampling velocity if the line diameter differs from the nozzle diameter. While it is desirable to keep the line diameter reasonably large, say 3/8 inches, to avoid clogging, a velocity sufficient to transport even the largest collected particles should be maintained. This means that the line velocity should be higher than the particle fall velocity and the lift

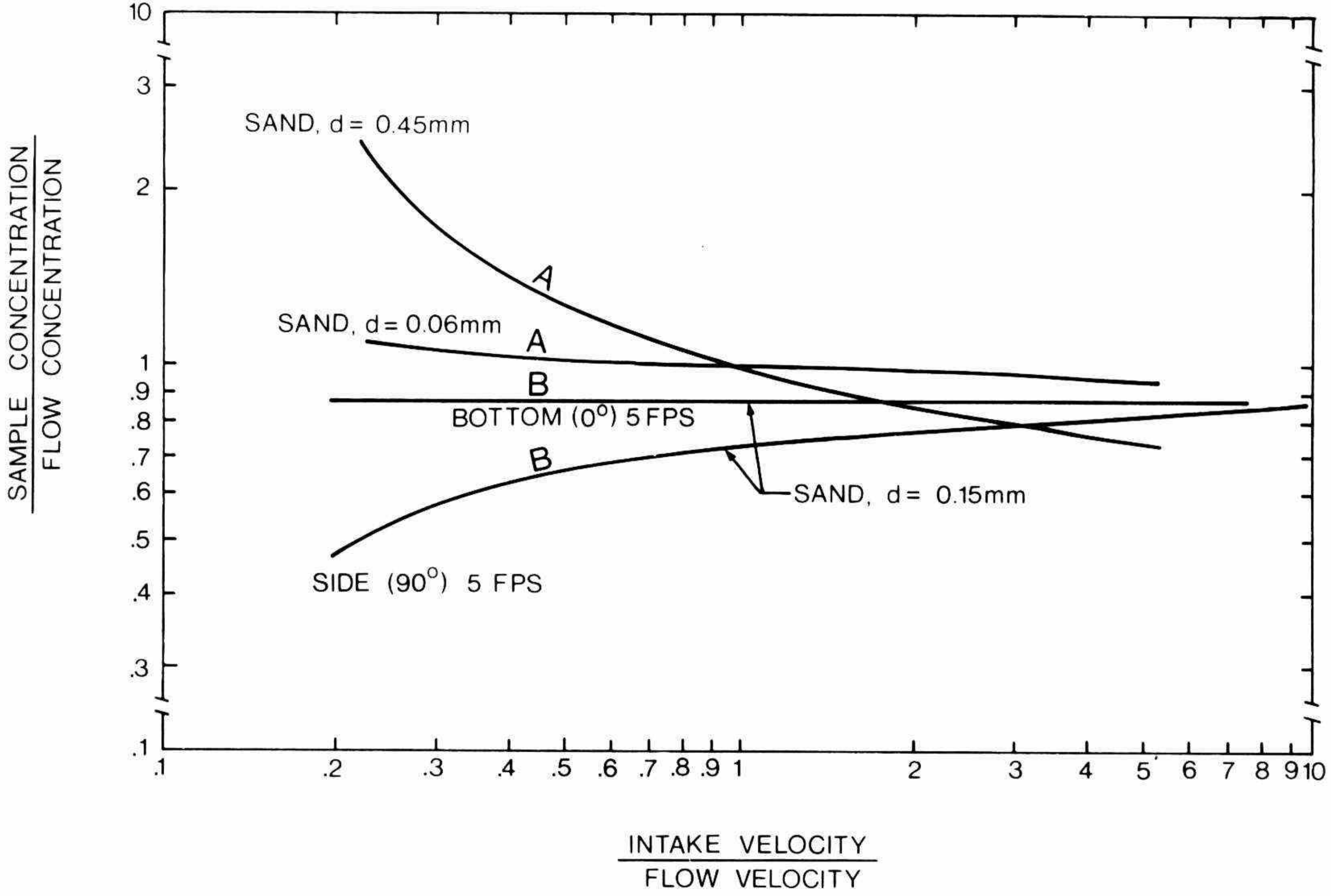


FIG. 23 A. EFFECT OF SAMPLING VELOCITY ON REPRESENTATIVENESS OF SUSPENDED SOLIDS*

B. EFFECT OF LATERAL ORIENTATION OF SAMPLE INTAKE* /*DATA FROM REF. 11 AND 19/

should be minimal. Even then the solid particles are transported upwards at a lower velocity then the ambient water particles, because the solids have a negative velocity (fall velocity) in relation to the ambient fluid. Therefore, the solids concentration in samples will be lower than that in the sampled media. This may be particularly significant in the case of large, heavy particles (see Figure 25).

The intake line velocity was determined for three samplers - Manning (S-4000), North-Hants and Sirco (Mark VII). The results are plotted in Figure 24. For common suction heads, say h = 1.8 m (6 ft), the intake line velocity was found to vary from 0.46 m/s (1.5 ft/s) to 1.24 m/s (4 ft/s). The highest line velocity corresponded to the intake line with the smallest diameter, d = 0.006 m (1/4 in). Such a small pipe may be susceptible to clogging by solids.

The effect of the intake line velocity on the solids distribution in a sample is illustrated in Figure 25. The distribution of particle sizes was adopted after ref. [30]. Subsequently, the transport of particles of seven various sizes was considered, assuming fall velocities corresponding to spherical sand particles. For the assumed solid particles distribution and line velocities varying from 0.15 m/s (0.5 ft/s) to 1.5 m/s (5 ft/s), the sampler efficiency of solids collection varied from 59% to 90%. The line velocity of 0.9 m/s (3 ft/s) was found acceptable and was available in the case of commercial samplers. For a different particle size distribution, the effect of the intake line velocity on the solids collection could be substantially different.

It should be stressed that all the above discussions apply mainly to sand-like particles (same shape and specific gravity). For lighter particles, the density effects described are less pronounced.

4.3.3 Sample cross-contamination

Cross-contamination of samples is another source of errors in sampling. It can occur because of deficiencies in the sampler plumbing, or because of residue in the intake line. The former possibility is uncommon and the residue in the intake line may be removed by an air purge preceding the sample withdrawal. Some commercial samplers have separate intake lines for each individual sample.

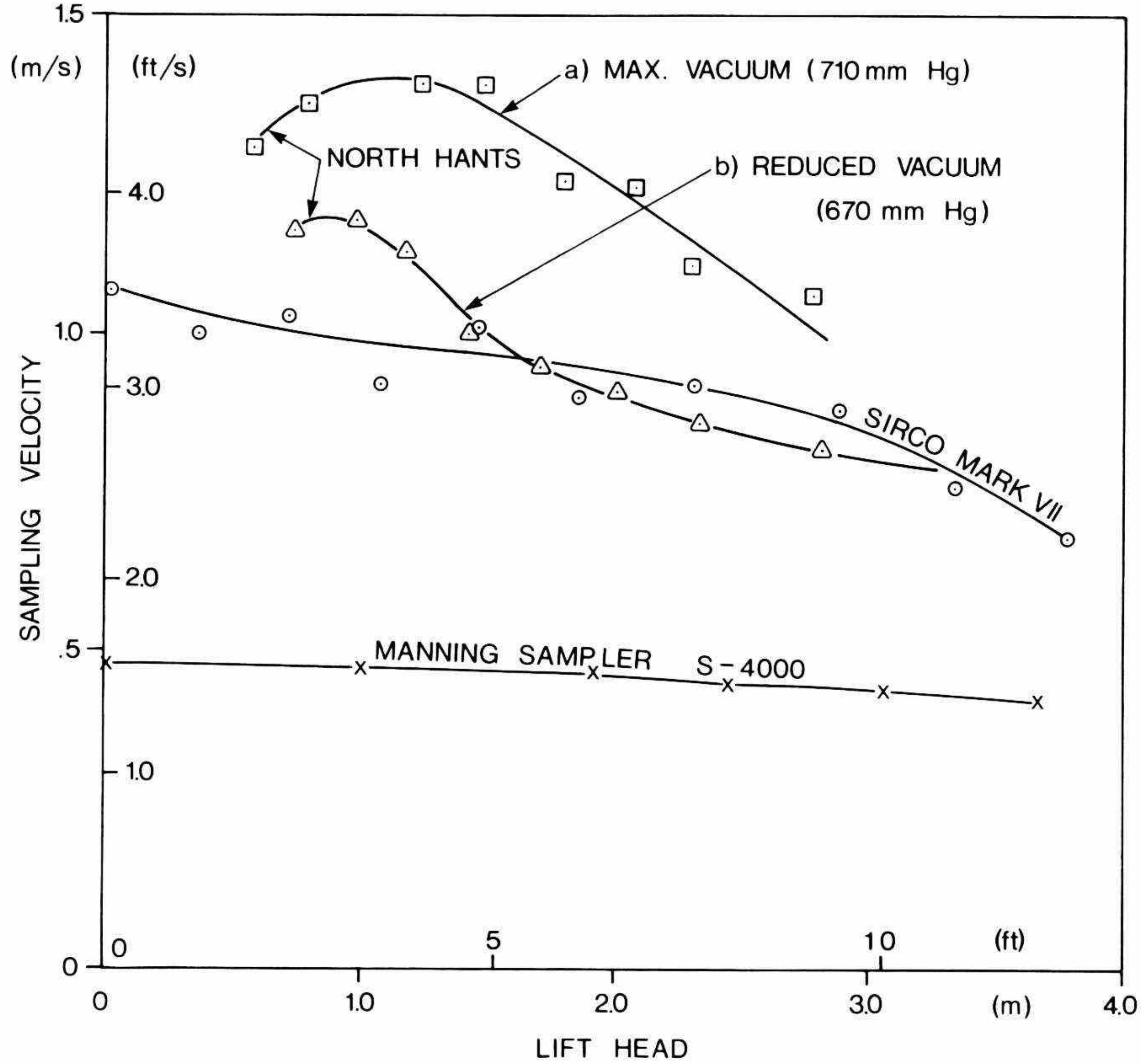


FIG. 24. SAMPLING VELOCITIES FOR THREE AUTOMATIC SAMPLERS.

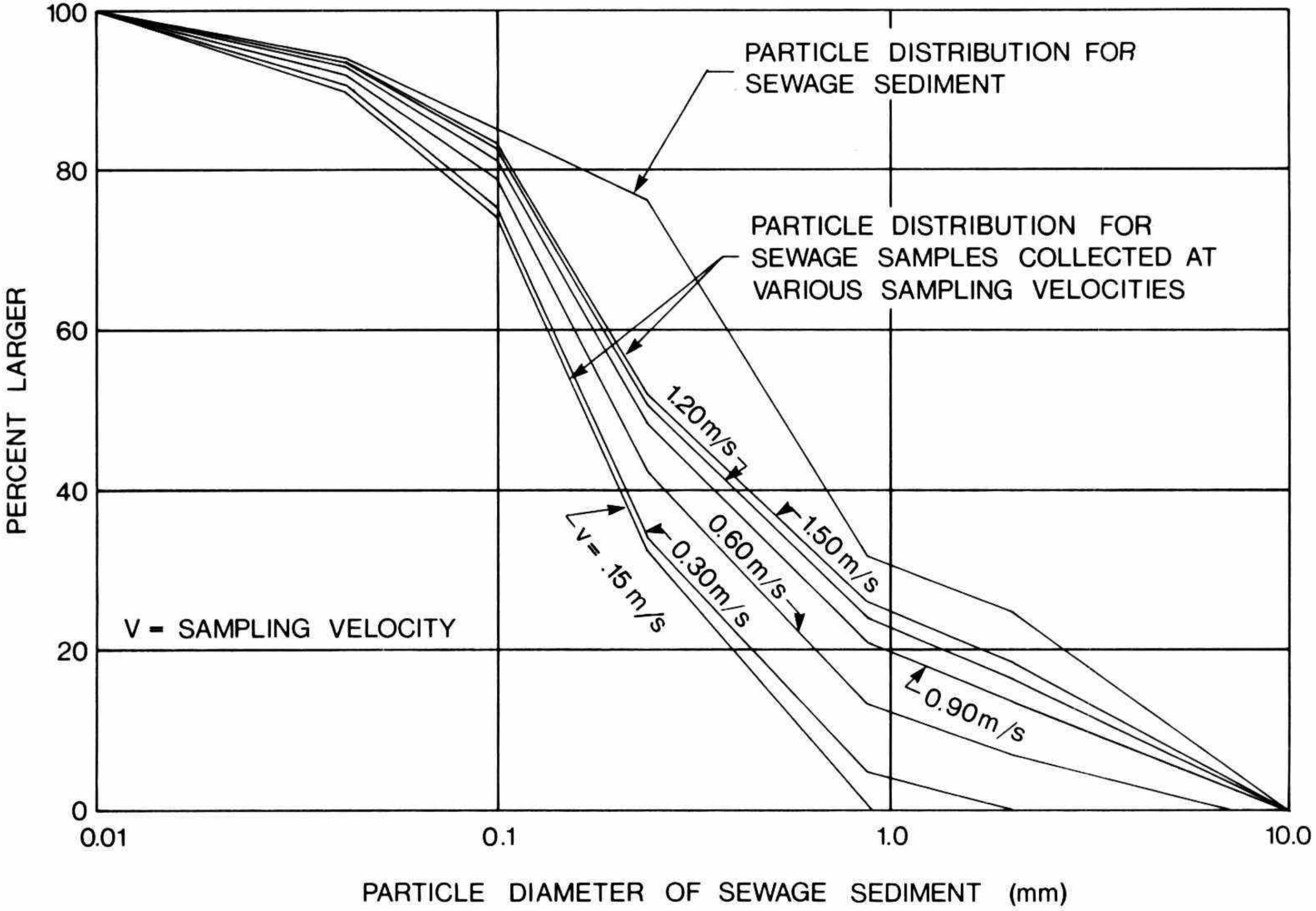


FIG. 25. EFFECT OF SAMPLING VELOCITY ON PARTICLE SIZE DISTRIBUTION IN COLLECTED SEWAGE SAMPLES.

4.3.4 Time synchronization between the sample withdrawal and flow recording

Poor time synchronization between the sample withdrawal and flow recording can cause appreciable errors in the calculation of the total pollutant yields, because incorrect pollutant concentrations will be assigned to the measured flow rates. The proper synchronization is best achieved by simultaneous recording of the runoff flow rates and sampling cycles on the same chart or tape.

The first sampling cycle should start as soon after the beginning of the runoff as possible. The sampling cycle can be triggered by the first impulse from the precipitation sensor, or better, by the rise of the storm water level in the sewer by a preselected increment.

4.3.5 Field experience with automatic samplers

Among the instruments used in urban runoff studies, automatic samplers are the least reliable. Malfunctions occur quite frequently even when these instruments are properly serviced and maintained. Consequently, two steps should be taken:

a) the sampler operation should be continuously recorded, and
b) to avoid frequent losses of data, two samplers may have to be operated in parallel.

In this study, four makes of automatic samplers were used: Manning Sampler S-4000, North Hants Liquid Sampler 4B-LT, SIRCO Portable Sampler MK-VS7, and SIRCO Sampler B/ST-VS/24A-EX. A brief summary of operational experience follows.

The Manning S-4000 is a portable vacuum type sampler. Samples, adjustable up to max. volume of 500 cm^3 (18 fl. oz.) are drawn by a high speed vacuum pump, battery operated. The sampler has two useful optional features - multiple samples per bottle and multiple bottles per sample. The former feature makes it possible to accumulate a number (up to five) of consecutive samples in one bottle before advancement to the next bottle. It will work in either time or flow mode. This allows even closer monitoring of runoff quality, e.g. by withdrawing small aliquots at short time intervals and composing them into a five-minute sample.

Multiple bottles per sample allows filling of up to four consecutive bottles (500 cm^3 each) in immediate succession. This is one way to increase the sample volume; however, the number of consecutive samples that can be taken is reduced.

The sampling cycle consists of a pre-sampling purge, the sample withdrawal and a post-sampling purge to avoid sample cross-contamination and to clear the sampler tubing. Up to 24 sequential samples can be collected at an intake line velocity of 1.5 ft/s (0.45 m/s). The sample collection is controlled either internally by a timer, or externally by a flow meter output signal. The sampler is typically powered by a 12V DC battery, or optionally, by 110 V AC.

The Manning sampler was operated at a storm sewer outfall for about four months. During this period, the sampler was found reliable and suitable for runoff studies. The relatively low intake line velocity (1.5 ft/s, 0.45 m/s) may be a drawback in some locations.

The North Hants sampler is one of the simplest automatic samplers on the market. It is a vacuum type sampler. The vacuum is created by means of a hand vacuum pump prior to the sample collection in the field. A timer opens valves in the individual tubes leading to the sample bottles, from which air has been evacuated. The withdrawal of the first sample has been triggered off by a signal from the liquid level sensor (Manning Dipper) when the storm water level rose by two inches.

The sampler operated reasonably well, if frequently maintained and attended. The major problem was the loss of vacuum which may occur if the sampler is unused in the field for an extended time period (say one week). It is recommended, therefore, that the sampler be checked in the field at least twice a week and, if a significant loss of vacuum is detected, the sampler should be checked for possible air leakage and the vacuum reset by the hand pump.

The North Hants sampler is suitable for runoff studies - it is relatively simple, compact, inexpensive, and up to 24 of 900 ml samples can be collected (for a maximum obtainable vacuum) at a fairly high intake line velocity (1.0 m/s). The NH bottle rack had to be modified (somewhat reduced), in order to insert the sampler through a standard manhole cover (diameter d = 22").

The Sirco MK-VS7 is a portable vacuum type sampler. The samples, adjustable up to max. volume of 500 cm^3, are drawn by a high speed vacuum pump, battery operated. The sampling cycle consists of a pre-sampling purge, the sample withdrawal and a post-sampling purge to avoid sample cross-contamination and to clear the sampler tubing. Up to 24 sequential samples can be collected at a fairly high intake line velocity (about 1.0 m/s for the lift of 2 m (6 ft)). The sample collection is controlled either internally by a timer, or externally by a flow meter output signal. The sampler is typically powered by a 12 V DC Battery, or optionally, by 110 V AC.

In this study, the sampler was initially operated in the battery-power mode. Frequent power failures occurred, even when installing fully charged batteries twice weekly. Later, the AC power was installed and used to power the sampler. Considerable improvement in the sampler operation took place.

The Sirco MK-VS7 is suitable for runoff studies provided that 500 ml samples are acceptable and a source of AC power is available. Without AC power, frequent recharging of batteries may be required.

The Sirco B/ST-VS sampler has similar features to the MK-VS7, only it collects 1000 ml samples and is consequently somewhat bulky. With the AC power, it worked fairly reliably and can be used in runoff studies.

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APPENDIX

Example of an Experimental Design for Sequential Sampling in an Urban Runoff Quality Study

APPENDIX

Example of an Experimental Design for Sequential Sampling in an Urban Runoff Quality Study

The experimental design technique is demonstrated in this paragraph on the urban runoff data adopted from ref. [5]. For a simple runoff event, i.e., with a single peak hydrograph, the pollutant concentration variation is assumed in the form of:

$$C = C_o \, e^{-K_2 t} \qquad (1)$$

where C is the pollutant concentration at time t

C_o is the initial concentration

K_2 is the decay rate (a constant)

t is the time lapsed since the beginning of runoff

For this illustration, the chemical oxygen demand (COD) was selected. The problem is to find the number of storm water samples to be analyzed to determine the parameters C_o and k_2 with a prescribed uncertainty (say 0.05) provided that the measurements of concentrations are made with an uncertainty K_c. The estimated uncertainty of C_o and k_2 can be predicted by the prediction analysis and would approximate the uncertainty determined by the least squares analysis of the actual data.

The uncertainty is defined here as the estimated value of the standard deviation. When the uncertainty is expressed in percent it will be referred to as the accuracy.

The detailed development of the prediction analysis equations for an exponential decay function is presented in ref. [36] only the modified final expressions are presented below.

Case I - The pollutant concentration is measured with a constant uncertainty ($\pm \Delta C$); the uncertainty in time recording is negligible.

The uncertainties for C_o, k_2 can be expressed as follows [36]:

$$\sigma_{c_o} = \frac{K_c (z_b - z_a)^{\frac{1}{2}}}{N^{\frac{1}{2}}} \left(\frac{2\{(z_a^2 + z_a + 0.5) - (z_b^2 + z_b + 0.5)\exp\left[-2(z_b - z_a)\right]\}}{D_1} \right)^{\frac{1}{2}} \quad (2)$$

$$\sigma_{k_2} = \frac{K_c\ k'_2 (z_b - z_a)^{\frac{1}{2}}}{C'_o N^{\frac{1}{2}}} \left(\frac{2\{1 - \exp\left[-2(z_b - z_a)\right]\}}{D_1} \right)^{\frac{1}{2}} \quad (3)$$

$$\sigma_{c_{o,k_2}} = \frac{K_c^2 k'_2 (z_b - z_a)}{C'_o\ N} \left(\frac{2\{(z_a + 0.5) - (z_b + 0.5)\ \exp\left[-2(z_b - z_a)\right]\}}{D_1} \right) \quad (4)$$

where t_1 is the real time when the first measurement was taken

t_n is the real time of the last measurement

K_c is the uncertainty of the concentration measurements

N is the number of experiments

k'_2 is an estimate of the magnitude of k_2 (this estimate may be crude)

C'_o is an estimate for C_o

$$D_1 = \exp(-2z_a)\{0.25 - (2z_a z_b - z_b^2 - z_a^2 - 0.5)\exp\left[-2(z_b - z_a)\right] + 0.25\exp\left[-4(z_b - z_a)\right]\}$$

$$z_a = k'_2 \left(t_1 - \frac{t_n - t_1}{2N} \right)$$

$$z_b = k'_2 \left(t_n + \frac{t_n - t_1}{2N} \right)$$

Case II - The pollutant concentrations are measured with a constant fractional uncertainty (±pC); the uncertainty in time recording is negligible.

The prediction equations for this case will read [36]:

$$\sigma_{c_o} = \frac{K_c\ C'_o}{N^{\frac{1}{2}}} \left(4 + \frac{12 z_a z_b}{(z_b - z_a)^2} \right)^{\frac{1}{2}} \quad (5)$$

$$\sigma_{k_2} = \frac{K_c k'_2}{N^{\frac{1}{2}}} \quad \frac{12^{\frac{1}{2}}}{z_b - z_a} \tag{6}$$

$$\sigma_{C_o, K_2} = \frac{6\ (z_a + z_b)}{(z_b - z_a)^2} \tag{7}$$

The notation is the same as in case I.

Equations (2) - (7) were applied to data from reference [5]. For this particular runoff event, the COD data is plotted in Figure A together with a least squares estimate for the COD variation during the runoff. After estimating C_o, k_2, Equations (2) - (7) were evaluated for a two-hour runoff event, the number of samples varying from 2 to 50. The results of these calculations are plotted in Figure B in the following form:

$$\sigma_{c_o} = A_1\ K_c = f(N) \tag{8}$$

$$\sigma_{k_2} = A_2\ K_c = f(N) \tag{9}$$

A brief examination of Equations (2) - (7) and results plotted in Figure B indicates that both uncertainties σ_{c_o}, σ_{k_2}, increase with the increasing error in the pollutant concentration measurements and the increasing range of the independent variable (time in this case). Both uncertainties decrease with the increasing number of experimental observations.

For both cases, I and II, the uncertainties in C_o, the initial pollutant concentration, are rather small. For the number of observations N=8, the uncertainties in C_o are smaller than those for the observations.

The uncertainties in k_2, the rate of decay, are considerable. If only the more typical case II is considered and the uncertainty of the concentration measurements is, for instance 0.10, then to estimate k_2 with a 0.05 uncertainty would require 17 experiments.

In some cases, the uncertainty of experimental observations can be reduced by using more sophisticated and more costly equipment. If cost curves can be developed for these different levels of experimental uncertainties, a minimal cost approach can be used for the selection of the number of experiments and the experimental uncertainty. An example

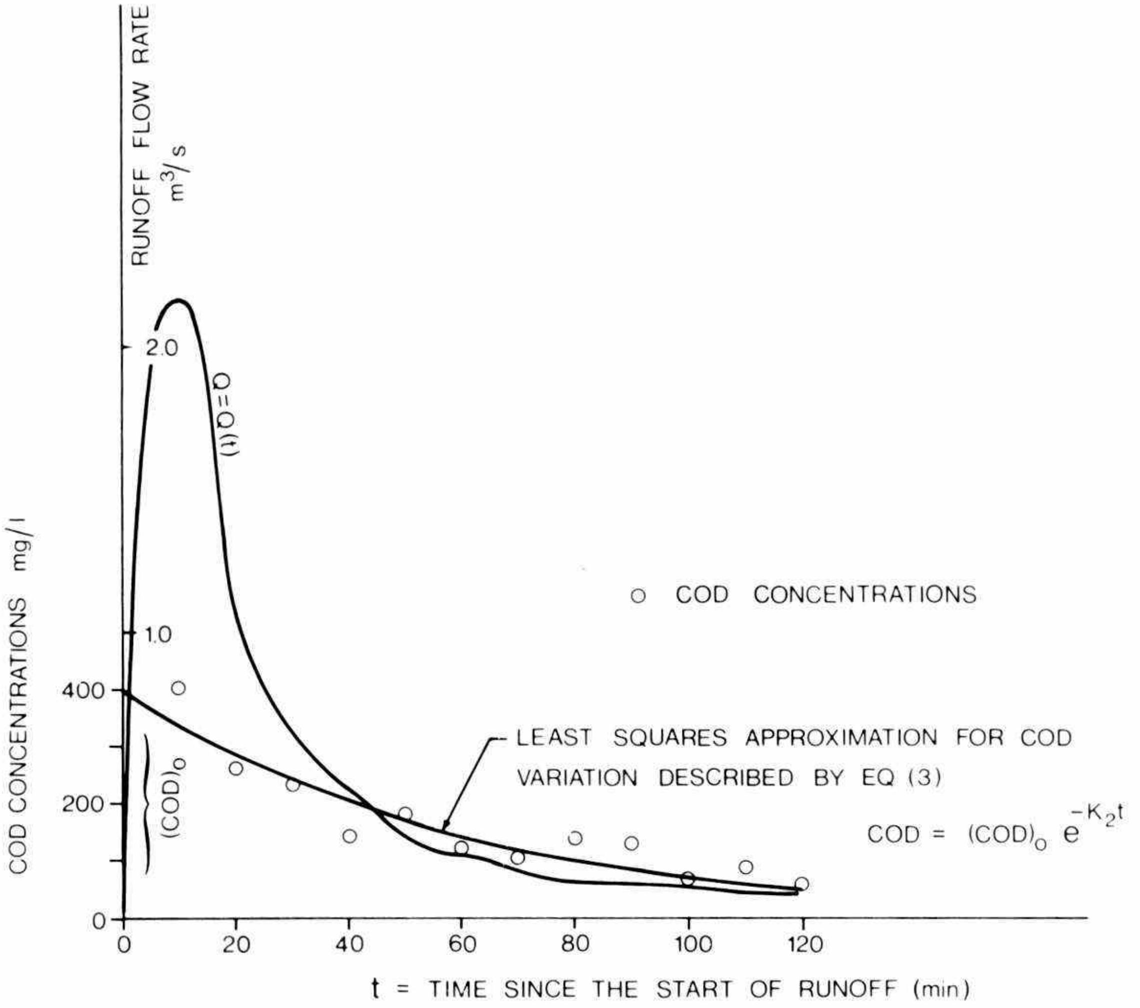

FIG. A APPLICATION OF AN EMPIRICAL MODEL TO RUNOFF QUALITY DATA (BASIC DATA - COD CONCENTRATIONS AND FLOW RATES - AFTER REF. 5)

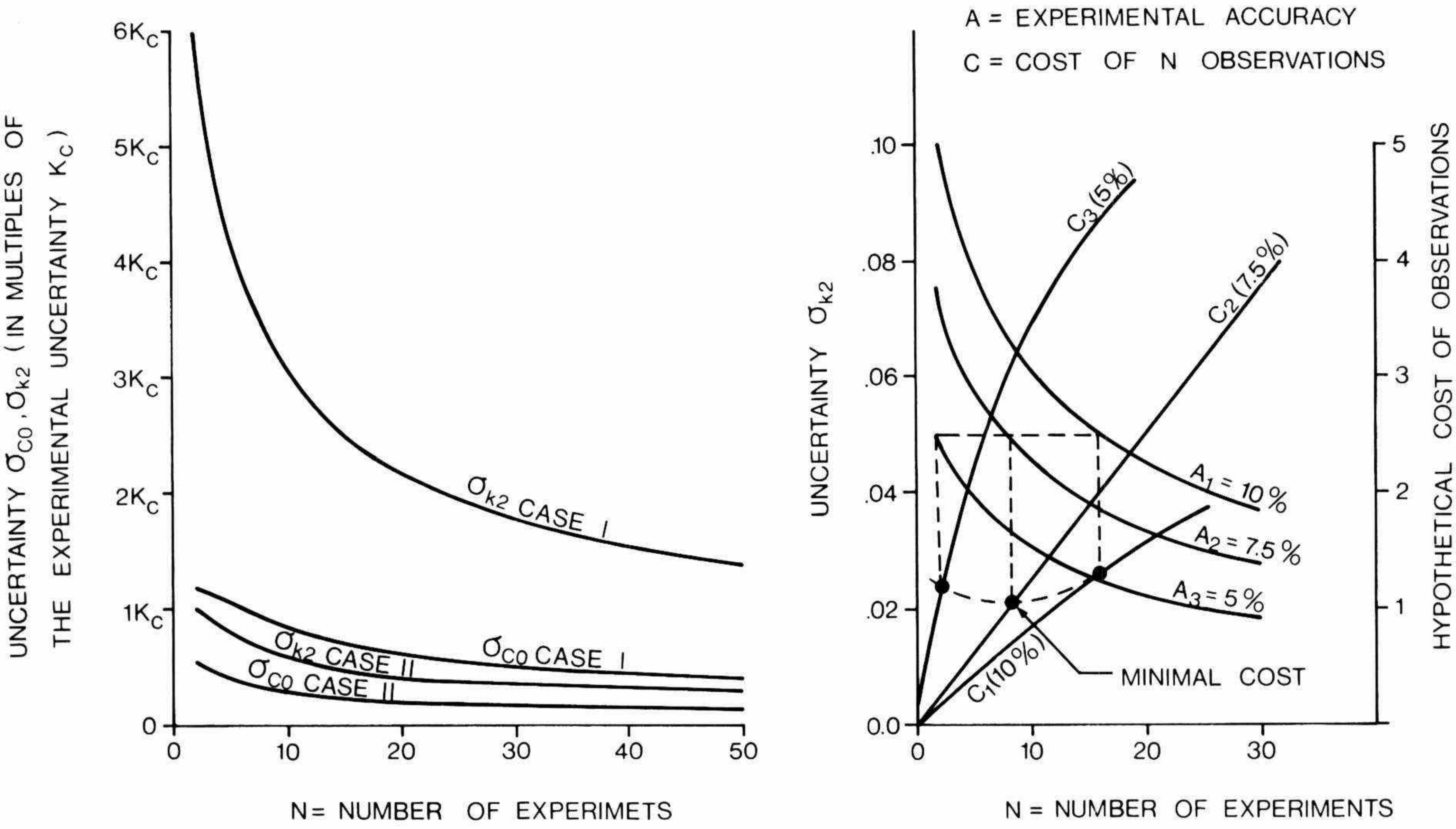

FIG.B APPLICATION OF PREDICTION ANALYSIS AND LEAST-COST APPROACH of this approach is shown in Figure B for hypothetical data. In this case, the cost curves were assumed for three levels of experimental uncertainty, 0.05, 0.075, and 0.10. If the desired uncertainty in k_2 determination is 0.05, then the cheapest alternative is to perform eight observations with a 0.075 uncertainty. Since most of the water quality analytical techniques are standardized, and consequently there is no freedom in selecting the experimental uncertainty, the above minimal cost approach would rarely apply.

The technique demonstrated in this appendix can be used for any functional relationship. The technique offers a good indication of the number of samples which have to be analyzed to obtain acceptably accurate data.

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